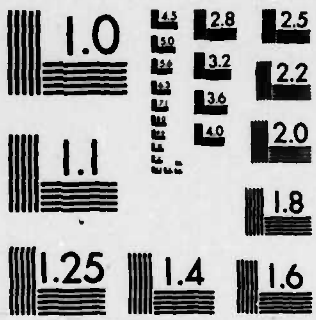
AD-A143 219 ARTIFICIAL INTELLIGENCE/ROBOTICS APPLICATIONS TO NAVY AIRCRAFT MAINTENANCE(U) SRI INTERNATIONAL MENLO PARK CA D R BROWN ET AL. JUN 84 SRI-4905 DTNSRDC/CMLD-CR-53-84 1/3

UNCLASSIFIED N00600-82-D-8362 F/G 5/1 NL



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June 1984

Final Report

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Contract No. N00600-82-D-8362 D.O. 0001
Report Period: 1 January 1983 to 30 April 1984

By: DAVID R. BROWN RICHARD H. MONAHAN WILLIAM T. PARK

Prepared for:

DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER
BETHESDA, MARYLAND 20084

REPORT No. CNLD-CR-53-84

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SRI International

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER CNLD-CR-53-84	2. GOVT ACCESSION NO. AD-A143219	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Artificial Intelligence/Robotics Applications to Navy Aircraft Maintenance		5. TYPE OF REPORT & PERIOD COVERED Final Report - 1 Jan 83 to 30 Apr 84
		6. PERFORMING ORG. REPORT NUMBER 4905
7. AUTHOR(s) David R. Brown, Richard H. Monahan, and William T. Park		8. CONTRACT OR GRANT NUMBER(s) N00600-82-D-8362 D.O. 0001
9. PERFORMING ORGANIZATION NAME AND ADDRESS SRI International 333 Ravenswood Avenue Menlo Park, CA 94025		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command Code AIR-310I Washington, DC 20360		12. REPORT DATE June 1984 13. NO. OF PAGES 214
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
14. MONITORING AGENCY NAME & ADDRESS (if diff. from Controlling Office) David W. Taylor Naval Ship Research and Development Center, Code 187, Bethesda, MD 20084		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Artificial Intelligence, Robotics, Navy Aircraft Maintenance, Cost-Benefit Models

Artificial Intelligence (AI)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The general objective of this study was to develop a data base and methodology of assessing AI/robotic applications to Naval aircraft maintenance. The research was conducted in three phases: Survey of AI/Robotics, AI/Robotic Opportunities and Design Concepts, and Cost-Benefit Methodology. Chapter II of this report presents a summary description of the AI/Robotic technologies that are relevant to Naval aircraft maintenance. The detailed survey of AI/robotic technologies is presented in Appendix A of this report.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. KEY WORDS (Continued)

20 ABSTRACT (Continued)

In Chapter III, various opportunities for application of AI/Robotics are discussed under different categories of automation such as information systems, interactive maintenance aids, etc. For each of these categories of automation opportunities, a number of specific maintenance design concepts are then identified. Each design concept is described and discussed in relation to the state-of-the-art in AI/robotics, and research trends and needs.

The methodology developed for assessing the cost-benefit tradeoffs of possible implementation of AI/robotic techniques and procedures directed to the enhancement of Naval aircraft maintenance system efficiency is presented in Chapter IV. The applicable cost-benefit factors are discussed and then a description of a cost-benefit model is presented. The use of the model is then demonstrated with the use of a hypothetical application. Appendix B presents a description of a utility data base structure for representing manpower requirements, which supports the cost-benefit methodology. The computer program that implements the cost-benefit model is listed in Appendix C, together with a description of the program inputs.

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PREFACE

This report documents the analysis and findings of a research project conducted for the David W. Taylor Naval Ship Research and Development Center (DTNSRDC), Bethesda, Maryland. The technical monitor was M.J. Zubkoff, Code 187, of DTNSRDC. The research was sponsored by the Naval Air Systems Command under the direction of D.S. Hurst, Code AIR-310I. The work was performed under Contract N00600-82-D-8362 D.O. 0001.

The research was performed within the following three organizational activities at SRI International:

- Systems Evaluation Center (SEC) of the Research and Analysis Division (RAD). L.L. Gilbert is Director of SEC, and D.D. Elliott is Vice President of RAD.
- Advanced Computer Systems Department (ACSD) of the Information Systems Consulting Division (ISCD). L.L. Fried is Director of ACSD, and D.H. Brandin is Vice President of ISCD.
- Robotics Laboratory (RL) of the Advanced Technology Division (ATD). D. Nitzan is Director of RL, and W.F. Greenman is Vice President of ATD.

R.H. Monahan of SEC was program manager and co-principal investigator. The other principal investigators were D.R. Brown of ACSD and W.T. Park of RL. M.A. Hackworth provided the computer programming support for this project.

SRI extends its appreciation to personnel of the Aircraft Intermediate Maintenance Department at the South Weymouth Naval Air Station, South Weymouth, Massachusetts.

I INTRODUCTION

This is a report on the potential for applications of artificial intelligence and robotics (AI/Robotics) to Navy aircraft maintenance at the organizational and intermediate levels. It is intended to be broad in scope, and it represents a preliminary look at the field of potential applications. The SRI project team has comprehensive knowledge of artificial intelligence and robotics, but was limited in the depth of its investigation of current practices in Navy aircraft maintenance at the organizational and intermediate levels. A one-day visit to the South Weymouth Naval Air Station on October 19, 1983, provided the SRI team its only field experience during the project. Nevertheless, this experience, together with knowledge already possessed by the SRI staff and knowledge gleaned from current Navy documents, provides a good basis for the purposes of the study.

The general objective of the study was to develop a data base and methodology of assessing AI/robotic applications to Naval aircraft maintenance. The research was conducted in three phases: Survey of AI/Robotics, AI/Robotic Opportunities and Design Concepts, and Cost-Benefit Methodology. Chapter II of this report presents a summary description of the AI/Robotic technologies that are relevant to Naval aircraft maintenance. The detailed survey of AI/robotic technologies is presented in Appendix A of this report

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II RELEVANT TECHNOLOGY

A detailed survey of relevant AI and robotics technology is presented in Appendix A of this report. A brief review is presented in this chapter.

A. AI versus Robotics Technologies

The types of tasks suitable for applications of AI/robotics technologies are, in general, tasks that are ordinarily performed by humans, since both AI and robotics are aimed at building machines that imitate human behavior. Artificial intelligence is concerned with the functions of the brain, whereas robotics include, in addition to brain functions, sensors and effectors. Even though the machines may imitate human behavior, important differences exist. For example, machines are far from having the capability of humans to understand language, recognize objects, or perform operations requiring great dexterity. On the other hand, machines have no fear, are tireless, may have great strength, can work in hazardous environments, and are constantly alert and able to function at their best.

Robots require artificial intelligence, but AI may be useful without robotics. (Some see robotics as a subdivision of AI.) In maintenance, or any task requiring both knowledge and manual dexterity, AI may possibly be helpful in supplying the knowledge required for the task. For example, a maintenance technician may be guided through his task by a computer with artificial intelligence, without the need for robotics. If robotics were used, the eyes and hands of the technician might be replaced by a robot, eliminating the need for a person to perform the task. Thus, we see two basically different approaches to the use us AI in aircraft maintenance. In the first, AI is used to provide knowledge to the human who actually does the work using his own

eyes and hands. In the second, AI (in the form of robotics) is used to do the work, eliminating direct human contact in performing the task. In this second case, either a human or a computer with artificial intelligence can guide the artificial eyes and hands (of the robot). If human intelligence is used to guide the artificial eyes and hands, the system is called a teleoperator. In general, developing an application that uses AI alone will be easier (i.e., it will cost less and require less from advanced technology) than developing one that uses robotics. Also, a teleoperator system will be easier to develop than one without a human operator.

B. Relevant AI Technologies

1. Expert Systems

Expert systems have attracted much attention in recent years and their usefulness has been demonstrated, especially in the case of the expert system, XCON, used by the Digital Equipment Corporation for configuring DEC VAX-11 computer systems. Expert systems are based upon a knowledge base of expertise, sometimes expressed as "if ..., then ..." rules. The expertise is derived from human experts, and makes that expertise as available as the computer on which the system has been installed. In the case of XCON, the system has had some unexpected benefits. One has been in the area of maintenance, where field maintenance has been made easier as a result of the consistent manner in which computer systems have been configured. Another commercial development has also attracted attention. The General Electric Company is developing a promising expert system for troubleshooting diesel-electric locomotives, called CATS-1. It incorporates the expertise of one human expert and is intended for repairs that can be made in the field in a few hours.

2. Automatic Planning

Planning systems, sometimes considered a kind of expert system, have not yet achieved the degree of acceptance and application that have

been achieved by expert systems. However, automatic planning has been a subject of research in AI from the beginning, since planning techniques are at the core of artificial intelligence. Planning is the creation of a sequence of actions that can be carried out to reach a goal. The potential advantages of automatic planning systems are that they can handle complexities beyond the ability of humans, and at far greater speed. Planning with multiple constraints is difficult for humans, and likely to contain errors, whereas automatic planning systems will always be correct (assuming the inputs are correct). The speed of planning systems makes them ideal for monitoring the execution of plans and rapid replanning when the situation changes. Automatic planning may be done completely autonomously (as in the case of an unmanned vehicle) or may be done interactively with a human supervisor.

3. Natural Language

AI research in natural language and speech is aimed at reducing the natural language (or speech) input to a representation in the computer that captures the intended meaning. In "understanding" speech, the input is a digitized acoustic signal, while in "understanding" natural language, the input is text, usually entered from a keyboard. Speech input has obvious advantages, since no typing skills are required and the person's hands are free for other tasks. While many problems remain to be solved, limited but useful natural language systems are already commercially available. The problem of understanding speech is much more difficult because of signal interpretation difficulties. However, usable technology for speech input has become increasingly available. Subsystems are now available that can "recognize" words, or even sentences spoken by different persons, subject to limitations in vocabulary and sentence construction. Experience with commercial natural-language interfaces to data bases, notably the INTELLECT system sold by the Artificial Intelligence Corporation, has proved the usefulness of AI-type natural-language technology. These interfaces can handle English grammar, in general, with the limited vocabulary of the data base to which they are interfaced and the limited function of retrieving specific facts.

4. Machine Vision

Vision is the most useful sense a maintenance robot can possess. It will allow the robot to identify, inspect, and determine the position of objects around it, rapidly, at a distance, and without touching them. In many situations the best (or only) method for a mobile robot to navigate will be by visual observation of its immediate surroundings.

Artificial intelligence research on machine vision today concentrates on imagery that has too much inherent variability for commercially-available industrial vision systems---e.g., noisy or blurred imagery, cluttered scenes, and objects that are only partially visible or whose shape cannot be precisely known (like trees). Office, shop, and outdoor scenes (especially urban) are extremely difficult for machine vision systems to analyze due to uncontrolled lighting, weather, dirt, and the tremendous variety of objects that can be seen.

Though concerned with interpretation rather than acquisition of images, much AI vision research is directed towards specific kinds of imagery, such as gray-scale, color, and various kinds of three-dimensional images. It is primarily concerned with segmenting an image into meaningful parts and identifying them. "Bottom-up" approaches start with the raw image data and attempt to segment it on the basis of local characteristics such as edges, shading, or texture. "Top-down" approaches start with descriptions of the kinds and groupings of objects to expect in a scene and attempt to find them. These two methods are complementary. For example, top-level information about object shapes can help eliminate spurious edges, while low-level features can provide possible outlines to match against the objects being sought.

The more unpredictable the appearance of the objects involved in a maintenance application, the more important artificial intelligence techniques will be for machine vision. For example, assembling a turbine or wheel from a kit of clean parts laid out on a table would probably require only a commercial industrial vision system. Disassembling a dirty or damaged one would be much more difficult. Visual navigation would be simpler on a clear runway or flight deck than in a shop area or belowdecks.

Three-dimensional imaging techniques will be particularly important in future robot systems. Much AI vision research has been expended on determining the three-dimensional shape of an object from 2-dimensional black-and-white or color imagery. For example, one approach is based on multiple two-dimensional images from different directions (binocular or motion stereo), another on analysis of shading variations across the object ("shape from shading"). It is becoming possible to avoid this kind of image processing completely and sense the three-dimensional shape directly. Two such techniques include structured illumination of a scene and measuring the round-trip time of flight of a scanning laser beam.

C. Relevant Robotics Technologies

The robotic technologies most relevant to naval air maintenance applications are manipulation, sensing, mobility, and control.

1. Manipulation

Manipulation technology consists of a well-developed body of kinematic theory for producing any desired movement of an end effector (e.g., a gripper or tool) carried at the end of a robot arm. The arm may be any size and shape, but for complete control of end-effector motion it must have at least six independent joints. More are needed if the arm itself must also get around obstacles.

Although most manipulators function as arms (i.e., they carry a "hand" of some sort), they can also be used as "necks" (carrying a camera) and "legs." Recently, multiple small, three-jointed manipulators have been mounted on a hand to produce true fingers In the near future we may expect to see the development of extremely small manipulators for micromanipulation, arms with a large number of joints ("tentacles") for getting into confined spaces, and dendritic (multiply-branched) manipulators for complex manufacturing and assembly tasks.

2. Sensing

A robot can of course carry and operate almost any kind of sensor that a task requires. However, only a few different kinds are needed by the robot itself, today. It is convenient to distinguish between robot-control sensors that sense conditions internal to the robot and those that sense external conditions. The latter can, in turn, be usefully classified as either contact or noncontact, depending upon whether or not the relevant transducer must touch another object.

a. Internal Sensors

The most common internal sensors in robots today are those for proprioception (sensing relative position of movable parts of the robot) and kinesthesia (sensing motion or effort in them). Their signals are rarely available outside of the servo control systems that regulate the motion of the robot's joints.

The most common proprioceptors are potentiometers, resolvers, and single- and multi-track encoders. These report the instantaneous position of a robot joint. The most common kinesthetic sensor is a tachometer that reports the rate of change of joint position. The effort at a joint is usually measured indirectly by monitoring current through the joint motor or pressure across a fluid actuator, though recent approaches use strain gauges in the joints.

In the near future, inertial sensors will be extremely important in mobile robots, for navigation. Fiber optic linear and angular accelerometers will probably be the most common kind, but a Japanese fluidic sensor also looks promising.

b. External Sensors

External sensors give a robot its sense of touch, sight, and hearing. Touch sensors are of course contact sensors, while the others are noncontact.

(1.) Contact Sensors

Contact, or tactile, sensors may detect touch or measure pressure, force, or torque. Good tactile sensing will be vital in achieving the degree of dexterity that robots will need to do many equipment maintenance tasks.

Touch sensors are usually used in fingertips to control and monitor grasping. Microswitches, strain guages, and conductive elastomers are usually used as the transducers.

When a robot is fitting parts together, it is very useful to be able to monitor the direction and magnitude of the force and torque that it exerts on the parts. The least accurate method is to measure efforts in the arm joints. A better approach is to measure the vector force and torque at a point in the wrist with a special six-degree-of-freedom moment sensor (now commercially available) and then mathematically transform them to the parts. A more recent and sophisticated approach is to measure the joint efforts in three servo-controlled fingers. It is also possible to mount force/torque sensors in jigs and fixtures. Strain guages are the most common transducer in this sort of tactile sensor.

Recently, fingertip-sized sensors have become available that can measure pressure distributions over a planar region about one inch on a side. These are called tactile arrays. They produce a kind of two-dimensional image which can often be interpreted successfully with conventional visual image processing algorithms. Tactile arrays will be very useful in the future for handling small parts. They can be used to identify the parts as well as to accurately determine how the fingers are holding them. A variety of innovative transducers are used in tactile arrays, such as conductive elastomers and integrated circuits.

(2.) Noncontact Sensing Modes

The most important noncontact sensing mode today is vision, though use of ultrasonics is growing rapidly.

Visual sensors can supply information at a faster rate (e.g., 4 MHz) and from a larger sensing volume (in principle, infinite) than any other. The most common kind of robot vision system today is a "binary system." It uses a monochrome television camera to take a picture that has a range of different brightnesses in it (a "gray-scale" image). It then increases the contrast to make dark objects in the scene stand out against a light background (or vice versa). Finally, it applies various simple and rapid measurements to the high-contrast ("binary") image to identify and locate the objects. A binary vision system can learn to recognize new objects by being shown them once, and can even recognize them if they appear in arbitrary orientations. However, the lighting must be carefully controlled or the high-contrast images will vary enough to be unrecognizable. Nevertheless, many different kinds of "benchtop" maintenance tasks could be set up to meet this requirement and a robot could do them.

Structured-light vision systems have become available for use with robots in the last few years. These do not require such strict control over ambient lighting as binary vision systems, and can provide three-dimensional information about part shape, often quite accurately. They allow a robot to perform a variety of inspection tasks important in maintenance, and can help it find parts that are too jumbled together for a binary vision system to see them.

The Polaroid ultrasonic range sensor has been on the market for several years now, and has often been used to detect the presence of objects around a robot and the distance and direction to them. More sophisticated forms of ultrasonic in-air sensor are now becoming available that will perform precise inspections and position measurements that the Polaroid sensor cannot.

3. Mobility

Though rare today, mobile robots will be crucial for many naval air maintenance functions, especially outdoor ones. Navigation and

propulsion are the most most important considerations. Navigation will require advanced technologies such as inertial navigation and three-dimensional machine vision. A simple wheeled mechanism, however, would be an adequate propulsion system for most naval air maintenance tasks. Future mobile robots will use AI methods to determine their location and plan routes to follow. Steering and short-range obstacle avoidance will require only good engineering.

4. Control

Control issues include the degree of autonomy that the robot has and the organization of the control software and hardware. Some naval air maintenance applications require only remote control of the robotic equipment, others a completely automatic mode of operation, and still others a combination of the two. Independently of these choices, the control system can be organized as an hierarchical set of processes, a set of interacting parallel processes, and located in from one to many computers. A number of techniques have been developed for reliable communication between different processes and computers, and these will probably be quite important in more complex robotic maintenance systems.

III AUTOMATION OPPORTUNITIES AND DESIGN CONCEPTS*

A. Opportunities

1. Categories of Automation

Some important classes of parts that we found are routinely maintained at intermediate level include engines, helicopter rotor hubs, wheels and brakes, hydraulic valves and actuators, scanning mounts for radar dishes, microwave and hydraulic "plumbing," and wire harnesses.

We have grouped opportunities for automation of naval air maintenance activities into the following categories:

IS -- Information systems
IM -- Interactive maintenance aids
AS -- Automated spraying systems
TO -- Teleoperated equipment
MC -- Mobile autonomous cleaning robots
DR -- Automatic disassembly and reassembly robots
IE -- Automatic inspection equipment
FR -- Fabrication robots

2. Equipment Descriptions

The type of automation equipment that would be used in each of these categories is as follows:

IS -- Information systems

Computer systems with advanced software that use artificial intelligence techniques to make decisions that would normally require a skilled, experienced expert.

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* Individual research is not generally cited in this chapter. Applicable references are included in the bibliography presented at the end of the main body of this report.

IM -- Interactive maintenance aids.

Computer systems with artificial intelligence software and special peripherals that make it easy for the computer and a maintenance technician to communicate with one another.

AS -- Automated spraying systems

Robotic equipment for spraying various liquids.

TO -- Teleoperated equipment

Remotely-controlled robotic equipment for performing hazardous or fatiguing tasks that are too difficult for robotic equipment to perform fully automatically.

MC -- Mobile autonomous cleaning robots

Robotic equipment to perform routine cleaning tasks of various kinds in various locations.

DR -- Automatic disassembly and reassembly robots

Robotic equipment that can automatically perform various functions involved in rebuilding various parts of an aircraft.

IE -- Automatic inspection equipment

Robotic equipment that can automatically carry out various kinds of routine inspections on aircraft components.

FR -- Fabrication robots

Robotic equipment that can perform various material-shaping functions.

3. Summary of Conceptual Designs

Within each of the above general categories we have identified specific maintenance activities that could be automated. For each activity, we have developed one or more conceptual designs for AI and/or robotic systems that could perform the activity. The conceptual designs that we have developed are the following:*

----

* These are discussed in detail in Section B.

IS -- Management Information systems

* Interactive maintenance scheduler.
* Automatic maintenance scheduler.

IM -- Interactive maintenance aids.

* Expert system for diagnosing avionics
* Expert system for diagnosing engine malfunctions.
* Expert system for coaching maintenance technician.

AS -- Automated spraying systems

* Cleaning
* De-icer
* Anticorrosion coating
* Decontamination

TO -- Teleoperated equipment

* Remote Handling Equipment
* Hazardous Spraying
* Inspection

MC -- Mobile autonomous cleaning robots

* FOV removal from runway/flight deck
* Shop/office floor cleaning
* Janitorial service

DR -- Automatic disassembly and reassembly robots

* Turbine rebuilding station.
* Wheel rebuilding station.
* Engine rebuilding center.

IE -- Automatic inspection equipment

* Robotic ultrasonic inspection system.
* Filmless X-ray inspection system.
* Robotic magnetic particle inspection system.

FR -- Fabrication robots

* Automatic tube bending system.
* Templateless drilling robot.
* Robotic arc welding station.

4. Approximate Cost/Benefit Ranking

The potential benefits to be obtained from using the above systems would include one or more of the following:

RS -- Reduced requirement for highly-skilled personnel.

IP -- Increased productivity (more work from the same number of workers).

IC -- Increased capacity (more repairs in a given time).

DR -- Decreased residence time of a component in the facility (resulting in shorter down time of the inducted component or aircraft).

IF -- Increased flexibility and adaptability of the facility to change the amount and type of work performed.

SA -- Solution of an existing or potential safety problem.

The amount of research and development effort that would be needed to field prototypes also varies widely, from almost none for the tube bender to a major, "Manhattan project" for the engine rebuild center. Figure III-1 below gives a rough indication of the relative benefits (unquantified) to be expected from the various automation design concepts above, together with their approximate development costs. The abbreviations used in this figure are explained in Table III-1. The concepts listed in Table III-1 are ordered first by the ranking of their benefits in Figure III-1 and then by their cost.

Figure III-1 indicates that expert systems (XPS) and automatic planning programs (APP) have a wider range of expected benefits than the others, from moderate to major. Although there is some overlap (due to artificial intelligence technologies common to both concepts), the latter will generally be more useful, but also more expensive to

Table III-1

CONCEPTS ORDERED BY INCREASING COST IN EACH BENEFIT RANKING

RANK 1

ERC -- Engine Rebuild Center

RANK 2

XPS -- Expert Systems
APP -- Automatic Planning Programs
TRS -- Turbine Rebuild Station

RANK 3

WRS -- Wheel Rebuild Station

RANK 4

ATB -- Automatic Tube Bender

AAW -- Automatic Arc Welding Robot
FXR -- Filmless X-Ray Inspection System
TDR -- Templateless Drilling Robot

UIR -- Ultrasonic Inspection Robot
RHD -- Remote Handling Devices
GPS -- General-Purpose Spraying Robot

JAN -- General-Purpose Janitorial Robot

RANK 5

MPI -- Magnetic Particle Inspection System

FOV -- Foreign Object Removal Robot for Airstrip

SOC -- Shop/Office Floor Cleaning Robot

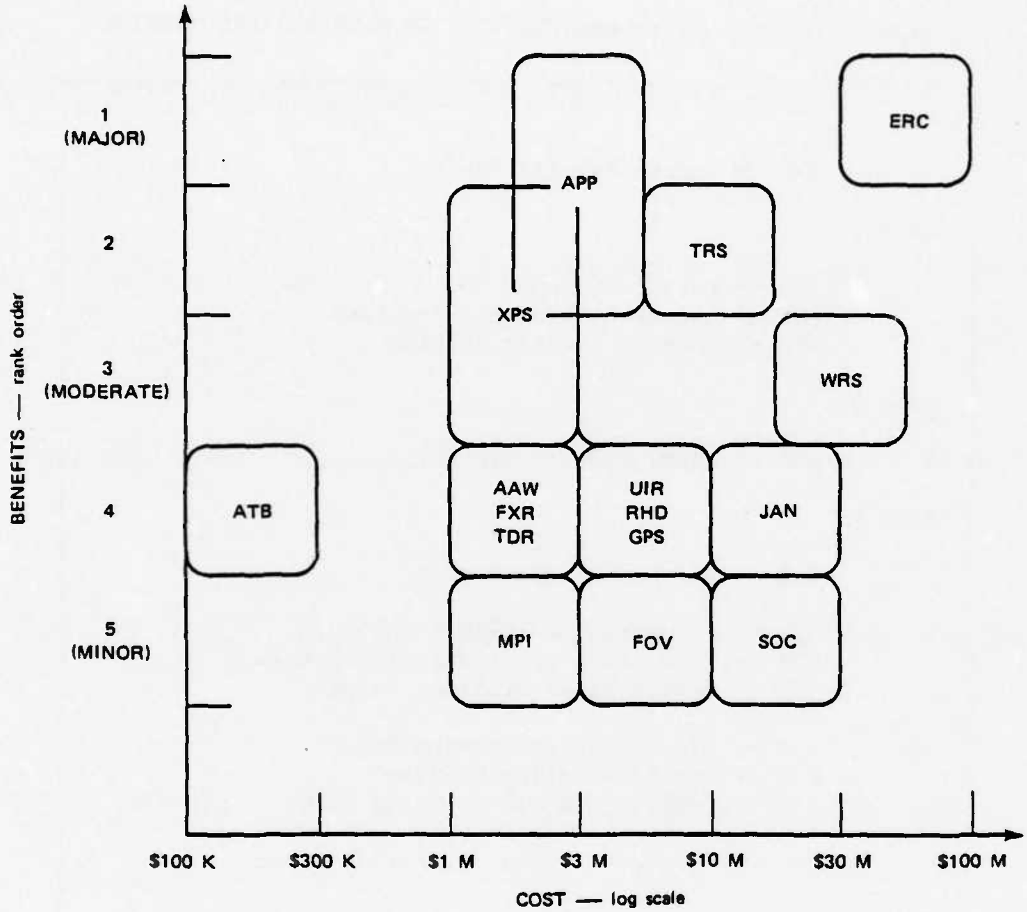

Figure 1 APPROXIMATE COST/BENEFIT SPREAD FOR PROPOSED MAINTENANCE AUTOMATION SYSTEMS

develop. Automatic tube bending (ATB) has the best cost/benefit ratio, followed by XPS and APP. Two of the rebuild centers---for turbines (TRC) and engines (ERC)---are also attractive, but much more expensive than several equally-attractive robotic systems for arc welding (AAW), X-ray inspection (FXR), and drilling (TDR). The mobile robot for cleaning up cluttered floors in shops and office areas (SOC) appears to be the least cost-effective concept to develop---a rather high-technology device to perform an unskilled job.

B. Automation Design Concepts

1. IS -- Management Information Systems

a. Interactive Maintenance Scheduler

The interactive maintenance scheduler would be a program that would help the maintenance/material control officer (M/MCO) to allocate time, personnel, and equipment so as to accomplish day-to-day maintenance mission goals. It would act as a "smart" assistant, bookkeeper, and secretary. The M/MCO would make the difficult, high-level decisions and then the program would fill in the details and do all the paperwork. The M/MCO might, for example, specify deadlines and priorities for making various aircraft airworthy, call out specific maintenance procedures to be performed, assign specific personnel to certain jobs, and inform the system of any maintenance equipment that is currently out of service. The computer program would do such things as assigning personnel to tasks based on a data bank of job package descriptions (skills, labor hours, and tool requirements for each repair), personnel availability, and skills certifications. It would generate any necessary documents such as duty rosters, routing instructions, maintenance equipment allocations, and orders for spare parts from inventory.

One of the most important capabilities for such a system to have would be the ability to accept "standing orders" from the M/MCO concerning the normal conduct of maintenance operations. This would allow the M/MCO to unload most of the burden of routine decisions,

scheduling, and paperwork onto the computer. Equally importantly, since every IMF is different, it would also allow him to tailor the system to the particular requirements and capabilities of the facility under his command.

Various expert-systems techniques would also be useful in representing the routine decision-making rules and judgmental criteria to be applied in day-to-day operations of the IMF. Since we cannot expect the M/MCO to be a computer expert, or even a typist, the system will also need a user-friendly "executive" style of interaction, involving some combination of voice I/O, touch-sensitive display screens, graphics, and the like that are becoming common in office automation hardware. Natural-language technology would probably be critical for user acceptance, too.

An important part of the M/MCO's job is the efficient scheduling of many diverse, overlapping activities in a sequence that makes sense. He must also try to eliminate from the plan any potential conflicts over people, equipment, floor space, or other limited resources. Wartime operations add further problems of intense time pressure, sudden changes in priorities and workload, and--especially on aircraft carriers--damage to the repair facilities themselves. AI technology for automatic plan generation will be required to solve these problems. In this design concept the M/MCO would make the difficult planning decisions, while the computer program would look after the low-level details to be sure nothing was left out. It would, for example, refine details of the maintenance plan automatically, keep track of remaining mission goals, estimate the time that would be needed to carry out the plan, and find and report any conflicts, slack, or bottlenecks. The computer can keep track of thousands of details automatically. This would would allow the M/MCO to evaluate several alternative schedules and pick the best, rapidly and without making mistakes.

Equally important, the same computer program could be used to monitor execution of the maintenance plan, based on reports from the shop areas. It could maintain a running prediction of readiness versus

time, identify developing problem areas, and issue status and activity reports.

Plan monitoring would also help greatly in revising a maintenance plan to react to some sudden change in the situation, such as equipment failure or a high-priority repair. The current status and work remaining would be already known, and the M/MCO could immediately begin to revise the schedule and reallocate resources to meet the new demands.

A plan generator produces as its output a diagram similar to a PERT chart. For each activity, the diagram shows which other activities must be completed before it can start, and which activities can commence after the activity is completed. The chart may also indicate various kinds of timing information, such as the expected duration of each activity, and the overall time to carry out the plan. It may indicate resource sharing between activities, consumables required, personnel assignments, or any other information of interest.

Plan generators have been a topic of research almost since the first days of artificial intelligence research. Today, however, plan generator technology lags considerably behind expert system technology in results. Plan generators are now at about the same level of development as expert systems were five to eight years ago. That is, they exist only as experimental research software, most can deal with only very simple problems, and no commonality in methods or design has yet emerged.

The reasons for the slow progress in this area are twofold. Firstly, plan generators have not yet performed well enough to attract the attention of venture capitalists, as expert systems have, so the available funds for R&D are much less. Secondly, putting together a correct plan is a much more difficult process than weighing evidence or applying a set of rules to facts in a data base in order to reach a single conclusion. Today's automatic planning methods are still basically trial-and-error, and AI research has concentrated on developing heuristic methods to minimize the number of errors. Some research topics in planning in recent years include the following:

- Divide-and-conquer strategies.
- Backward chaining.
- Interactive planning.
- Hierarchical planning.
- Automatic plan debugging.
- New representations for plans and planning domains.
- Experimentation with new languages (QLISP, PROLOG).

Plan generators could be used in maintenance planning to help a person to make the following kinds of decisions:

- What activities must be performed?
- When should each activity be performed?
- What people should be assigned to each activity?
- What material and equipment will be required and when?
- What tasks will be delayed if a given task takes longer than planned?
- How long will repairs take?
- What will the state of readiness be at any given time?
- How should the plan be revised if a vital piece of equipment should fail or if higher-priority repairs should become necessary?
- What additional resources would speed up repairs the most?
- How could damaged aircraft be cannibalized to result in the maximum number of serviceable aircraft?

At present, expert systems and plan generators are two distinct areas of research. There is little commonality either in the methodologies used in those areas or the people who work in them. It is clear however, that much is to be gained by merging the two technologies. This will probably not occur until the performance of plan generators improves a good deal over present levels—perhaps another five years.

Another important cross-fertilization that is likely to occur will be the merging of plan generator technology with traditional operations research (OR) methods. OR offers many powerful methods for searching among large numbers of alternatives, which is a fundamental problem in

many AI domains, including plan generation. OR, however, is best suited to dealing with quantitative or numeric aspects of a problem, whereas AI is better for the qualitative or logical aspects.

b. Automatic Maintenance Scheduler

This design concept is a more powerful version of the interactive maintenance scheduler described above. It would be able to make most of the high-level decisions that the M/MCO has to make for the interactive version. In addition to the normal bookkeeping functions of that system, this one would need a very sophisticated kind of expert system--more advanced than present-day systems, certainly.

The AI problems in implementing it would be, firstly, to understand how a skilled M/MCO makes decisions, and then to find ways of representing what he knows and ways of mimicking his decision-making processes with a computer program. Current expert-system methods such as rule-based and evidential reasoning would certainly play a part in such a system. But the scope of the problem is much larger and more varied than present-day technologies can deal with.

2. IM -- Interactive Maintenance Aids

Expert systems to aid in diagnosing equipment malfunctions are the most important applications we identified in our study. If automatic test equipment (ATE) is developed to make use of artificial intelligence techniques, it will be more widely applicable and more effective than today's ATE can ever be.

So far, ATE has been most successfully applied to diagnosing failures in avionics equipment. We found that it has been less successful in diagnosing problems in mechanical or electromechanical equipment such as aircraft engines and hydraulic systems, for reasons discussed below.

Commercial implementations of expert systems are already being used in the field to diagnose malfunctions in such complex electromechanical

equipment as diesel-electric locomotives [Johnson and Bonissone, September 1983] and oil-drilling machinery [Smith and Baker, 1983]. But, it is important to realize that these early successes are making use of only the first fruits of AI research. About twenty years and thousands of man-years of effort were required on fundamental AI issues such as knowledge representation, deduction and natural language in order to produce today's expert systems. There are many more research results in the pipeline that, when they reach the development stage, will result in expert systems that can solve much more difficult real-world problems. Diagnostic expert systems, in particular, will then be able to truly understand how a piece of equipment works so that it can plan and carry out test procedures as well as a skilled human mechanic. It may take ten or twenty more years for this level of performance to be achieved at the present rate of research.

Many of the limitations of present-day ATE stem from the fact that it has no real understanding of how the equipment that it is diagnosing operates. It merely runs through a sequence of tests that were designed, perhaps years previously, by the manufacturer of the ATE, the manufacturer of the equipment, or both, when the piece of equipment was developed. Some ATE systems can skip tests, depending on the results of preceding tests, to avoid wasting time testing subsystems that are working properly. But even in these systems, every detail of this "test logic" must be thought out carefully by experts and meticulously programmed into the ATE's control program.

Today's ATE is quite unable to determine whether a set of tests for a piece of equipment is complete or incomplete, correct or incorrect, or poorly designed. This can be a problem because equipment in service is often modified in dozens of different ways without updating the ATE test procedures to match (since that would require scarce, expensive, and highly-skilled software specialists). Consequently, today's ATE often fails to identify "obvious" problems. Worse, it may wrongly identify a problem, resulting in delay, expense, and waste of material before a person can discover its error.

Another limitation is that today's ATE is completely unable to devise new tests to diagnose problems in a piece of equipment that the equipment's designers did not foresee. Most ATE diagnostic software is, in fact, designed to detect only single-component failures. The number of components in most pieces of equipment is so large that the number of multiple failures that are possible is too astronomically large even to enumerate. This is not so serious in peacetime, since then most failures tend to result from individual parts simply wearing out. Battle damage, however, often results in both multiple failures within individual modules and simultaneous failures of multiple modules. This can make today's ATE systems ineffective just when they are most needed at organizational or intermediate maintenance levels. At depot level it can lead to wholesale scrapping and replacement of module contents to save time or to be on the safe side.

ATE has been more successful in diagnosing problems in avionics than in electromechanical systems because individual tests on purely electronic equipment usually take much less time. One reason is that the ATE can often set up electronic equipment for a particular test completely automatically, just by sending electrical signals to it. On the other hand, setting up a piece of electromechanical equipment for a test often requires physical activity such as turning valves, connecting or disconnecting parts of the machine, and operating manual controls in various ways. Even if the ATE were equipped with the best robot arms available today, they would not be dextrous enough to replace a human technician. This means that much more skilled labor is required to use ATE on non-avionic equipment.

Non-avionic ATE tests usually take much longer, too. They may have to wait for components to heat up or cool down, pressurize or depressurize, or go through a mechanical cycle. Also, it is impractical to instrument mechanical equipment with diagnostic sensors to the degree that avionic equipment can be. Therefore, tests on such equipment tend to require much more manual attachment and removal of test probes and guages, more manual operations on the equipment itself, and more human

interpretation of test results. Such tests may also consume scarce or expensive materials and tie up equipment that is needed elsewhere.

For these reasons, one test on a piece of electromechanical equipment may take as long and cost as much as several thousand tests on a piece of purely electronic equipment. Individual tests on avionics are therefore cheap, and this leads to the major reason for the success of ATE in that domain today--it is practical to use inefficient, "brute force," or exhaustive methods of diagnosis that would not be cost-effective on mechanical equipment.

Since it is unlikely that individual tests on non-avionic equipment can be speeded up very much, the number of tests must be minimized, and the information obtained from each test must be maximized. Therefore, if ATE equipment is to find problems in aircraft engines, helicopter drive trains, hydraulic systems, and weapons rapidly and cheaply enough to be as useful as it is now in avionics, it will have to be much "smarter" than it is today.

a. Expert System for Diagnosing Avionics

Expert systems, or knowledge-based systems, have been developed for applications in diagnosis and interpretation, such as MYCIN for medical diagnosis and DENRDAL for the intrepretation of data from mass spectrograms. However, other areas of application such as planning and design are promising, and also maintenance, especially since diagnosis is a part of maintenance. Although no applications in these other areas have yet proved to be of great value, several are being developed and the potential value of these systems may be very great indeed. Within the area of maintenance, expert systems may be advantageously used in any of a number of tasks, including fault diagnosis (in scheduled or unscheduled maintenance), and correction of faults. The expert system may be based on "shallow" or "deep" knowledge (i.e., the knowledge may be empirical or it may include knowledge of the inner workings of the subject).

For our study of the application of AI and robotics to Navy aircraft maintenance at the intermediate and organizational levels, the current activities in research and development of expert systems for maintenance applications should be noted.

One early research project, at MIT, was a program called EL that could simulate the operation of an electrical circuit and deduce the possible cause of a failure. The work at MIT on fault diagnosis using causal reasoning has continued and was reported by Randall Davis as recently as August, 1983, at the National Conference on Artificial Intelligence [Davis, 1983].

At the Navy Center for Applied Research in Artificial Intelligence, an ongoing project, called IN-ATE, is an expert system for guiding a novice technician in troubleshooting electronic equipment [Cantone et al., 1983].

The use of artificial intelligence in a general-purpose, logistic-support system for diagnosis and maintenance has been proposed by Boeing Aerospace Company. Their system, MDIS (Maintenance and Diagnostics Information System), encompasses diagnostics, maintenance (both preventive and otherwise), maintenance training, data collection, data analysis, and graphics [Antonelli, 1983].

General Dynamics has a prototype expert system for maintenance called IMA (Intelligent Maintenance Aid) that can be used for diagnosis of the Microwave Stimulus Interface (MSI) of the F-16 Avionics Intermediate Shop [Hinchman and Morgan, 1983].

DART, an ongoing, joint, IBM-Stanford University project, uses a causal model of a computer for fault diagnosis.

DELTA, or CATS-1, is a developmental expert system for troubleshooting diesel-electric locomotives. It is being developed by General Electric and is a shallow system, incorporating the expertise of a human expert. This system is now being field tested [Johnson and Bonissone, September 1983].

Bell Labs is currently developing an expert system called ACE (Automated Cable Expertise) for telephone-cable maintenance. ACE identifies trouble spots based on data from trouble reports, and suggests the repairs to be made [Vesonder et al., 1983].

Lockheed is developing a general-purpose expert system called LES (Lockheed Expert System). One application planned for LES is diagnosing faults in a network with switches controlled by signals distributed over a base frequency band.

Raytheon is developing a shallow expert system for fault diagnosis in electronic systems.

Martin Marietta is also developing an expert system for fault isolation.

The Naval Air Engineering Center has a contract with RCA to study the use of artificial intelligence in automatic test equipment. The report, to include a survey of all current applications of AI in ATE and an assessment of the future applicability of AI in ATE, will be due in June, 1984. The study has found that although automatic programming techniques using AI are many years from being practical, expert systems may have utility in the software development process [Kunert, 1983].

Some of these, and other AI systems for maintenance, were described at the Joint Services Workshop on Artificial Intelligence in Maintenance at Boulder, Colorado, in October, 1983. The invitational workshop attracted a much-larger-than-anticipated crowd, attesting to the importance of the subject. At that workshop, the problems in developing software for ATE were noted as being especially costly and time consuming, and the use of AI in development of software for ATE was recommended as one way of alleviating the problem.

Considering the amount of activity and the promising performance of a few prototype systems such as GE's expert system for troubleshooting locomotives, the use of expert systems in maintenance appears to be on the verge of being practical and useful. The expert systems closest to being useful are shallow, rule-based systems that use the expertise of

human experts. Expert systems employing causal reasoning are potentially more powerful, but their practical realization is some time away, probably several years. In aircraft maintenance, situations undoubtedly exist in which such shallow, rule-based systems could be profitably applied now. The criteria for such systems are fairly easy to define, and the useful applications could be found using such criteria. One important criterion, for example, is that a human expert must exist and be working in such a manner that automating him (or her) would make sense. On the basis of what we have seen, maintenance of avionics and aircraft engines are the most likely domains for immediate applications of expert systems.

The CATS-1 system, being developed by General Electric, appears to be a good model for a useful expert system in the area of avionics maintenance. It is aimed at diagnosis and repair of the problems that can be fixed in the field in two hours or less, appropriate for organizational and intermediate levels. By limiting the area to field maintenance, the complexity of the system has also been limited. The field prototype of CATS-1 incorporates 530 if-then rules and the final version is expected to have about 1200 rules. The system is being designed for field use, using a microprocessor and being programmed in FORTH. The system includes a video disk so that the steps in diagnosis and repair can be illustrated for the technician. It has been designed to require minimum verbal response from the technician, mainly "yes" or "no." As mentioned previously, the key to the success of the application appears to have been finding a human expert who was doing a job that could be usefully automated.

A rule-based expert system for troubleshooting avionics could be useful, particularly at the organizational level, for quick repairs in the field or on board ship. The system would be useful at the very first report of trouble, and facilitate repairs that can be made rapidly in the field. The scope would need to be broad, emcompassing the entire avionics suite of an aircraft type or configuration. An application would have to be found for which an expert presently exists. The

hardware-software system would be rugged and portable, with software that could be specialized to any one of a number of aircraft. The expert system could be similar to GE's DELTA/CATS-1, requiring minimum input from the user technician (primarily "yes" or "no"). The objective would be advice to the technician on how to repair the problem and return the aircraft to service.

In order to develop a successful system, some care should be exercised in selecting the application. Finding an avionics suite for which a human expert exists is essential. At the same time, the application would not be suitable if such experts were plentiful and readily available. The advantage of such an expert system would be in making readily available the expertise required to rapidly repair the avionics and return the aircraft to service.

b. Expert System for Diagnosing Engine Malfunctions

This would be an expert system that would deduce likely causes of engine failure from engine symptoms and test results supplied by a maintenance technician. It would take the form of a computer program, perhaps running in a rather small, even portable, computer. It would make use of a large data base (say, 1 to 10 megabytes) of expertise concerning the particular engine. The expertise particular to a specific engine would be kept on a demountable mass storage unit such as a cartridge Winchester disc platter. The technician would only have to insert the disc for the kind of engine he was working on.

The system could also have a videodisc and color television for showing the technician malfunctions, test procedures, diagrams, menus of options to select from. It could even play symptomatic engine sounds. The technician might even wear a small helmet-mounted audio/video display so that he could work on (or even in) the engine as he communicated with the system.

The system would take the place of a skilled maintenance expert trained on that engine, coaching the technician through the diagnosis. It would allow the less-experienced technician to find out what is wrong almost as well as the expert.

This is a rather low-risk design concept, since commercial equipment malfunction diagnosis systems very similar to it are already in late stages of development [Johnson and Bonissone, September 1983]. Head-mounted displays of the type described have also been tried in such applications [Riley et al., 1983].

Commercial systems do not, however, have much ability to explain the reasoning behind their conclusions about the reason for a failure, or why a particular test should be made. "Canned" explanations can easily be provided, of course, but only to the limits of the system developer's patience and budget. It cannot compare with having a human expert to query, since it is impossible to anticipate every possible question. Nevertheless, that is probably the most appropriate approach to employ in order to provide an explanatory capability in this design concept.

A more powerful, but higher-risk and higher-development-cost variant of this design concept would include what is called in AI terminology a "causal model" of how the engine works. This would provide the basis for a general question-answering facility, since it would enable the system to really "understand," in the usual sense of the word, how the engine operates. This would be almost as good as having a human expert who could answer whatever questions the technician came up with.

Also, a system able to answer arbitrary questions about such matters would also provide the core of a teaching system. In fact, it could teach not only diagnostic procedures, but the theory of the engine's operation, and perhaps even how to take it apart, repair it, and put it back together.

Causal models and how to use them to answer questions are still leading-edge research issues in AI today, however. The level of effort required to field a prototype system that "understood" how an engine worked would be quite large. And, the techniques required would, when developed, be applicable to far more than just engine diagnosis. So, the ability to make an expert system "understand" a specific machine

like a P-3 engine is something that we should expect to be able to add later, after basic AI research has made understanding machinery possible in general.

c. Expert System for Coaching Maintenance Technician

A more ambitious maintenance aid would coach a technician through the repair of an engine, once the nature of the failure has been diagnosed. It would need AI technology for plan generation in order to decide which parts to remove and in what order, and how to put them back. The actual repair step might involve replacement of a bad part, or some more complex process such as cleaning out a clogged tube. It shouldn't make any difference to the system, since it only has to explain what to do to the technician. He supplies any dexterity, sensing, judgment, and so on that is needed. This makes such a system much easier to develop than a robotic system to carry out the same repair.

For efficiency, the system should adapt to the technician's skill level by giving him instructions with only as much detail as he really needs. If he asks "How?," the system should be able to provide more detail, perhaps to several levels. For training purposes, it should be able to explain "why," too, so it will need such advanced capabilities as causal models, natural language generation, and question-answering.

This system has to generate a correct, complicated, multistep plan (and perhaps revise it, too, since the technician may break something or start taking the wrong parts off). So, it will be a much more costly system to develop than the simpler, purely diagnostic coaching system, which merely has to choose the most likely reason for a malfunction. Again, it will have to depend on breakthroughs in general AI research rather than a specific development effort.

3. AS -- Automated Spraying Systems

All the proposed systems in the spraying category are quite similar. In fact, it may be possible to design a single piece of

robotic equipment to do all the various jobs. Whether the increased speed or efficiency obtainable by specialization would outweigh economies of scale obtainable by generality is impossible to answer without detailed engineering design studies and cost/benefit analyses. Certainly there are a number of commercial spraying robots that could perform many of these functions immediately with little or no engineering effort.

Rather than describe several similar systems, we will merely say that what are needed are robot manipulators to spray various kinds of liquids onto objects. Fixed or oscillating spray heads can do some of these jobs more or less successfully. Fixed heads are usually most suitable for spraying large, smooth objects of the same shape and size (such as one type of aircraft). Oscillating heads are often used to spray medium-sized parts of different shapes (as in automatic spray booths). A spraying robot is more suitable for spraying large objects of many different shapes (such as many different shapes and sizes of aircraft), complicated shapes (interior of a wheel well), and things that have to be sprayed very carefully (as in painting or decontaminating them).

Some of the materials that we found are now being (or could be) sprayed in intermediate maintenance facilities are the following:

- Paint stripper
- Paint, dope
- Cleaners (detergent, solvents)
- De-icer
- Anticorrosion coatings
- Bleach (for decontamination)
- Abrasives
- Steam

Various conditions under which these materials are often used make them suitable candidates for spraying by robotic equipment. These conditions include the following:

- Skillful application required for proper or complete application, conservation of material, etc.
- Large variability in shape and size of objects sprayed.

- Need to travel to the object to be sprayed, especially outdoors.
- Hazardous nature of the object or the material being sprayed.
- Frequent need to spray similar objects.

Conventional commercial spraying robots consist of a manipulator and controller. The controller, even if it has a computer in it, is usually quite limited in its capabilities—i.e., it merely serves as a kind of "tape recorder" for arm motions. The controller cannot, for example, adjust the recorded spray gun trajectory to suit an object that is slightly out of place. Automotive manufacturers are investigating the possibility of automatically deducing the arm motions required to paint an automobile from shape information in a computer-aided design data base. In practice, however, to train a spray-painting robot a skilled human sprayer must grasp the spray gun at the end of the robot arm and spray one object with it while the controller records the arm's motions. One or two brands of spraying robots now offer a separate, light training arm so that the trainer does not have to move the heavy robot arm around.

We propose a modular robotic spraying system that would have some advantages over conventional designs. The system would include the following kinds of modules:

- A controlling computer, capable of operating several manipulators simultaneously.
- One or more manipulators of different sizes and shapes.
- A mobile base.
- A remote control device for training spray procedures.
- A variety of spray nozzles and pumping equipment for different substances that can be used with any arm.

Different combinations of modules could be connected together to perform different kinds of spraying tasks. Several long-reach spray arms could be controlled by a single computer to clean or decontaminate whole aircraft. A single arm might be used to steam-clean an engine to be disassembled. An arm on a mobile base could go out to the flight line to de-ice aircraft waiting to take off.

If an IMF performs a highly-variable mix of spraying tasks, such modularity could reduce the total capital investment in spraying equipment. Using spraying robots would reduce the danger in tasks like spraying anticorrosion liquids into a running engine. The training arm could also be used as a remote control to perform hazardous manipulation tasks as discussed the following section on teleoperation.

4. TO — Teleoperated Equipment

The term "teleoperation" dates from the early days of radioactive material handling. Then it referred to a person outside a "hot cell" operating mechanical "slave" arms inside the cell by moving full-scale "master" arms. When electrical connections between master and slave replaced the original mechanical ones, "bilateral force feedback" (BFF) had to be provided in the servomechanisms so that the operators could continue to feel what the slave hands were touching. Today, "teleoperator" means any remotely-controlled device that is not operated "blindly." Other forms of feedback than BFF are often used, now, such as a tv image or a computer-simulated display of the device. This is especially true when the device is something other than an hand, such as a camera on an arm, or a mobile robot.

Remote control in general is an important concept in robotics for several reasons. First, machines should do many jobs not because people are too scarce, expensive, or inaccurate but just because the job is too dangerous or strenuous for people. Then automatic operation is not necessary, and a remotely-controlled machine is often the simplest, most effective and economic solution.

Robotic technology can make it easier to operate a remotely-controlled device. A supervisory computer in a mobile robot, for example, can navigate, steer around obstacles, control speed, etc. so that the operator only has to tell it where to go. In a remotely-controlled arm, a computer might "learn" highly-repetitive or precise motions from the operator and carry them out automatically for him whenever they were needed. Or, it might use signals from tactile and

proximity sensors in the arm to decide when to override the operator's command and prevent a collision that could do damage.

Another reason for the importance of teleoperation is that it is often a good "first step" in developing a fully-automatic, computer-controlled robotic device. It allows experimentation with equipment and procedures before the control software is developed. This can save money, and reveal misconceptions about how the software should work. Then, too, the teleoperated system itself may prove to be enough of an improvement to be worth using in the field until the automatic system is developed. In some applications, it may be possible to increase the amount of automatic control capability in stages, gradually phasing out the human operator. This may be easier than developing a fully-automatic system in one step. An intermediate stage (a "computer-augmented teleoperator") may even be the desired goal for some applications.

The opportunities for using teloperated equipment in intermediate maintenance can be categorized as remote handling, hazardous spraying, and inspection. All three categories require a robotic manipulator of some sort, but each requires a different kind. Handling requires a rather large, strong, precise manipulator arm, but it does not have move fast. Spraying (hazardous or not) typically requires a fast-moving arm, but it does not have to lift much weight or be very accurate. Many different commercial robot arms would probably be quite suitable for most applications in both of these categories. The third category, inspection, requires an unusual type of manipulator that is not yet available--the "snake" or "tentacle" type of manipulator. Last year, Spine Robotics AB of Molndal, Sweden introduced a manipulator of this general type that has eight joints [Schreiber, February 1984]. Toshiba also introduced one with sixteen joints that has become known as "the elephant's nose" [Hartley, March 1983]. Neither of these manipulators, however, is flexible enough to perform the inspection applications we identified.

a. Remote Handling Equipment

A number of handling tasks in intermediate maintenance could be performed remotely using some sort of remotely-controlled robot arm. In order of approximate difficulty of implementation, they are the following:

- Tires
- Engines
- Hazardous chemicals
- Ordnance
- Ejection seats

(1) Tires

An aircraft tire, particularly a large one, presents a significant hazard since its carcass can rupture and its wheel can fracture. The resulting explosion can easily kill a person standing beside the tire.* A tire is most dangerous in the shop while being inflated, and a steel cage around it provides adequate protection. On the airplane, however, the tire is most likely to explode during or immediately after landing (when friction with the runway and heat conducted from the brakes have combined to raise internal pressure and weaken the carcass). The ground crew, for their own protection, may check the temperature by placing a hand on the tread and sliding it towards the wheel.

Tires have to be moved to and from storage racks, cleaning baths, bead breakers, and aircraft landing gear. Relatively simple, non-robotic, handling equipment (e.g., "load balancers") would be very useful in handling the larger tires.

(2) Engines

Engines are handled by slings on cranes and sometimes by fork lifts. Proper placement of the sling is important and slings must be regularly inspected and certified for weight-carrying ability. Each sling is designed for one type of engine. Installation of an engine in

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* An A4 main tire inflated to 200 p.s.i. for bead setting stores over 100,000 foot-pounds of energy.

an aircraft is a hazardous, operation with great potential for damage to both.

A specialized teleoperated manipulator with bilateral force feedback could be developed to handle several different kinds of engine. It would have two advantages over present handling methods. Firstly, damage would be less likely because the operator could feel any forces acting on the engine. During critical placement procedures such as installing the engine in an aircraft or in a test stand the operator would be able to feel if it got hung up on anything as it was being moved into place, feel it make contact, and feel whether it was properly seated. The magnitude of the forces acting on the slave arm would, of course, be scaled down and/or limited to a comfortable range (say, 20 pounds, maximum) in the master arm.

Hazards to the aircraft might be lessened as a result of the operator's being able to feel what is happening. When lifting an engine into place with a fork lift, for example, the lift operator has very limited control over the engine's motion, and little ability to tell if it is hitting something. Another person guiding the lift operator may not notice a collision, either. can easily apply excessive force to an engine mount or other structure in the wing without realizing it. He does not have good control over the engine's motion, either. Either the operator's own sense of feel or (potentially more accurate) continuous computer monitoring of loads on the slave hand could prevent this sort of accident.

Hazards to personnel might be lessened, too, if the tactile feedback to the operator allows him to position the engine accurately on its mounts. Then it would not be necessary for anyone to climb in beside the engine in order to lever it into place or guide the crane operator.

The main technical problem in this design concept is the design of the "hand" of the slave manipulator. The technology exists for building and operating the manipulator proper, though it would have to be scaled up somewhat from industrial designs to handle large engines. The hand

would have to be able to grasp engines of different shape and size without damaging them. Ideally, it should be able to grasp and hold an engine firmly while it is still in the aircraft (difficult, since there is not much room around the engine in some aircraft).

(3) Hazardous Chemicals

Hazardous chemicals handled in intermediate maintenance include liquid oxygen (LOX), volatile solvents, and acids. Handling includes normal transport of containers, transfer through hoses, and cleanup of spills.

LOX is mainly used in relatively small quantities for crew oxygen, and the main hazard is tissue damage from freezing as a result of contact with LOX itself or with equipment (e.g., hoses and tanks) that has been cooled by contact with it. Support of combustion is seen as a minor problem, except perhaps in confined spaces on shipboard.

Solvents and acids are sometimes used in quantity for paint stripping, corrosion control, and specialized cleaning. Some IMF's relegate large-scale activities of this sort (including painting) to depot level. Spraying these substances is more dangerous than using them in dip tanks. Sealed carboys and drums of hazardous chemicals present two kinds of hazards: slow leaks and the possibility of dropping them in handling. Damage results from contact with personnel or equipment, fume inhalation, and fire/explosion.

The benefits to be obtained by teleoperation methods to handle these substances include reduced personnel exposure and perhaps more reliable handling (due to reduction of fatigue and the ability of mechanical handling equipment to operate in the presence of spills, fumes, etc.).

We have not developed specific designs for teleoperator equipment to handle hazardous materials. Commercial robot manipulators could probably be used effectively as slave arms in many cases. Many are in daily use in explosive atmospheres, spray-painting booths, shot-cleaning booths, and other difficult environments.

When handling moderately-dangerous materials, the operator could simply stand a safe distance away and observe the robot directly. In more dangerous situations, such as large-scale spraying operations, or major toxic or corrosive spills, he would probably watch through closed-circuit television.

(4) Ordnance

Ordnance presents a pure handling hazard as well as its inherent explosive hazards. It is heavy, personnel often have to work rapidly, and many of the items have to be precisely positioned against and secured to mountings in the aircraft. To help in the latter activity, some IMF's go so far as to invent and construct specialized lifting and positioning machines. Even so, it is still necessary for a person to enter a bomb bay to oversee the correct placement and hookup of the ordnance, which places him in a pinch point. Marine specialists often perform critical tasks in ordnance handling on naval IMF's.

Teleoperator equipment similar to that described above for engine handling might be useful in arming procedures. The benefits and design considerations are quite similar. The same equipment might even be used for both purposes. More likely, though, the ordnance handling version would have to be much smaller.

(5) Ejection Seats

Ejection seats present a difficult maintenance challenge. They are hazardous because they contain a large, dangerous explosive charge. The cockpit is quite crowded, and considerable dexterity is required to carry out some tests and repairs.

Because of the extreme access problems, dexterity requirements, and difficulty of using visual sensors in a cockpit, we propose a teleoperator system for ejection seat maintenance mainly as a "high-end" automation challenge. The major benefit would be increased safety. Miniaturization and general performance improvements to existing BFF teleoperator manipulator technology is probably the main technical

challenge. Some other major problems include strengthening of manipulators, development of an effective man-machine interface for the operator, increased sensitivity of force-feedback, and probably development of multifingered slave hands with force feedback on each joint. It might even be necessary to provide tactile array sensitivity on some of the fingertips and feed that information back to the operator, too.

Like the other high-cost, high-risk design concepts mentioned in this report, the ejection-seat repair teleoperator is really an example of breakthrough technology, most of whose benefits would come from its use in a wide variety of other applications. It could be used to carry out scientific experiments in space satellites, operate nuclear fuel reprocessing plants, maintain undersea installations, or any activity where human hands and eyes were needed but could not go.

b. Hazardous Spraying

We identified at least three hazardous spraying applications in IMF's. They are

Spraying chemicals into the intake of a running engine
Decontamination
Firefighting

(1) Spraying into Running Engines

For corrosion control and de-icing, it is occasionally necessary to spray various chemicals directly into the air intake of an engine while it is running. There is a danger of being sucked into the engine that could be averted by using a spraying robot, probably a mobile one.

(2) Decontamination

In wartime it is possible that an IMF would have to deal with aircraft returning from a foreign theater of operations contaminated by chemical, nuclear and/or biological agents. This must be completely removed in order that normal maintenance activities can be carried out

without major disruptions to standard operating procedures, such as having to wear biohazard suits in the maintenance shops.

Although it is relatively easy to remove the contamination with fluids such as hot bleach, it is critical to treat all parts of the aircraft that may have been dirtied. The exterior of the fuselage is easy to clean, but the interiors of wheel wells and bomb bays present more problems since there are many places where a lethal agent could reside that are difficult to reach with a simple spray pattern (e.g., a "car wash" type of airplane cleaning facility). It will be necessary to go inside the well or bay and spray from many different positions and in many different directions. This is strenuous work, and a person in a rubber biohazard suit can only work at a small fraction of his unsuited rate due to heat loading.

Teleoperated spraying robots offer a solution to this problem. A person could stand comfortably in one place in his suit on the runway and direct a spraying robot working up inside the wheel well or bomb bay. If closer inspection is necessary, he could ride in a cherry picker. Teleoperation may in fact be preferable to fully-automatic spraying: Damage and variations in internal equipment from aircraft to aircraft of a given type might cause an automatic system to miss some spots.

The interior of an aircraft could also become contaminated. This presents a much more serious problem, but is more likely to be of the nuclear kind than chemical or biological (the latter are most likely to be deposited on the outside of grounded aircraft during an air or artillery attack). Nuclear contaminants can be removed by crews in respirators and simple protective clothing. It would be quite difficult to design a mobile robot--teleoperated or not--that could negotiate the crowded interior of an aircraft. CB Contamination of other internal portions of an aircraft, such as wing spaces, is particularly troublesome. The "snake" arms mentioned earlier might be of some help in getting into those areas with decontaminants.

(3) Firefighting

Suppression of fires in grounded aircraft is also a spraying operation, but with higher pressures and flow rates. Heavy-duty versions of teleoperated decontamination sprayers would be required. A local water spray on the robot itself for protection from the flames would probably be advisable, and might also shelter escaping personnel. Smoke would make it difficult for the operator to see the robot, or to see through television cameras on it. Alternative imaging methods based on infrared, microwave, or ultrasonic transducers might be more useful. A propulsion system would be needed to approach the fire. To keep that mechanism simple and reliable, it might be operated by a hydraulic motor driven by the same high-pressure fluid that is being sprayed.

c. Inspection

Teleoperators would be useful for inspecting areas in an aircraft that are difficult to get to, unpleasant, or hazardous. Some examples include wing spaces, fuel tanks, and ejection seats. Wing spaces are difficult to get into and contain many dangerous pinch points. Fuel tanks are usually full of lethal fumes. The fuel itself is flammable, often poisonous, and may have to be completely drained to allow inspection. Ejection seats present an explosion hazard.

An extremely useful kind of teleoperated robot for these sorts of inspections would be a long, flexible "snake" with an appropriate sensor in its "head," such as a television camera. It might be carried coiled up on a drum on a wheeled cart. Its operator would first steer its "head" into a convenient opening in the aircraft being inspected, such as an access port, cable run, or even a shell hole. Then, watching the image on the television monitor, he would guide the robot the rest of the way to the location to be inspected.

A teloperated robot like this would be able to get into tighter places than a person, would be unaffected by fumes, and would allow the inspector to remain in a safe location. Much less disassembly or skin breaching would be necessary to provide access for some inspections.

This sort of teleoperated inspection robot would need limberness more than speed, accuracy, or rigidity. Ideally, each segment of the robot would automatically follow in the tracks of the preceding segment as it advanced into the aircraft. To be useful, the "snake" inspection robot would need dozens, perhaps hundreds of computer-controlled joints---far more than in any existing robot arm. Nevertheless, it could probably be developed with moderate extensions to existing technology.

5. MC -- Mobile Autonomous Cleaning Robots

We found several opportunities for an IMF to use robotic equipment for routine cleaning operations. These include :

- Foreign object removal from runway/flight deck
- Shop/office floor cleaning
- Janitorial service.

Because of limitations on the number of civilians that may be hired, some IMF's must assign skilled crewmen or reservists to these routine, unskilled tasks. Robotic equipment to perform these functions would allow better use of manpower.

Paradoxically, these "unskilled" jobs are among the most difficult to automate, because of the inherent unpredictability of the working environment. The list above is arranged in order of increasing difficulty. Only the technology for the easiest, foreign object removal, is in hand now.

a. FOV Removal from Runway/Flight Deck

This design concept is a mobile, autonomous robot capable of traveling over a runway or flight deck, finding objects that could cause engine problems if inhaled by an aircraft, and collecting them for later disposal. For a relatively small cost, additional equipment could be added to the basic system so that it could perform the additional functions of

- Cleaning up oil spills
- Spreading special chemicals such as de-icer or foam
- Location and marking of potholes
- Renewing painted markings
- Bird dispersal.

Such a device would increase safety by reducing the number of people in the taxi and takeoff areas. The problems of navigation, propulsion, power supply, low-level control of the machine itself, and high-level control from the flight operations center are straightforward engineering problems. The main risk would be development of sensors, effectors, and control methods that could reliably detect and deal with foreign objects. A "first cut" would be to equip a commercial sweeper/vacuum with an on-board minicomputer and simple navigation equipment.

b. Shop/Office Floor Cleaning

This design concept would be a much smaller version of the FOV removal system. Its primary duty would be to clean floors while its main benefits would be productivity improvement and, in some cases, better use of skilled personnel. The main risks are in the development of an adequate sensing and control system. It is another example of a generally-useful robot that could be used in many other places than the IMF.

A typical shop or office is a very crowded and complex environment for present-day mobile robots. To simplify the problem, it would be easier for the robot to operate only at night when there are fewer people around. Even so, a number of difficult "common-sense" control problems have to be solved, such as

- Getting through closed and/or locked doors
- Going up and down stairways
- Distinguishing between trash and non-trash (such as papers that have fallen off a desk)
- Not getting caught on electrical cords for office equipment
- Getting under and around furniture to reach trash.

Mobile robots currently used in office environments have very simple control systems that are completely inadequate for this task. They follow fixed marked paths, move slowly, and merely transport materials instead of affecting their surroundings. They can, however, summon and use elevators.

This type of robot would probably be less useful on shipboard, where excess labor for menial tasks is usually present.

c. Janitorial Service

This design concept is a more ambitious version of the floor-cleaning robot. It would also be able to empty wastebaskets, wash and wax floors, clean lavatories, vacuum rugs and do windows.

6. DR -- Automatic Disassembly and Reassembly Robots

The following design concepts all represent very advanced forms of robotic and AI automation for direct use in repair of specific, non-avionic aircraft systems. They address the problems of surge capacity, shortage of critical skills, and productivity. In order of increasing development cost and risk, the aircraft parts that these systems would rebuild are:

- Turbines
- Wheels
- Engines.

a. Turbine Rebuilding Station

This concept consists of one or two robot manipulators together with associated sensors, effectors, computers, and auxiliary tooling. It would accept turbine rotors and/or stators, take them apart, inspect the components, replace damaged components, and reassemble and inspect the rotor or stator.

The problems addressed by this design concept include productivity, surge capacity, and shortage of critical skills. The development cost

would be high--perhaps 10 million dollars, if existing robots could be used, and individual stations might cost a million or more dollars each. However, much of the technology would be generally applicable in manufacturing and repairing a wide variety of other equipment, both military and commercial.

The main technical risks lie in the development of appropriate programming methods and tooling to perform certain high-force or high-accuracy tasks for the robot arm(s). Robotic hardware development as such would probably be minimal. Most of the time the arms would be used merely to handle small parts. The most difficult assembly action is probably the insertion and removal of the individual turbine blades, for which special tooling could do the job if the arms couldn't. Some automated inspection techniques would have to be developed to verify correct assembly; some research has already been done on automatic inspection of blade integrity. Part of the rebuild process involves precise metal removal, for stator i.d. and for rotor balance. Automating these processes could require a significant R&D effort.

Turbines are the simplest of the three aircraft components in this group to rebuild because they consist entirely of precisely-shaped, rigid parts. The disassembly operations are largely insertions, with limited use of fasteners. Precise tolerances are involved, and 100% correct assembly is vital (both requirements that make a job a good candidate for automation).

Although certain components, such as turbine rotors, may be sent back to depot level to be rebuilt, the stator as well as the rest of a jet engine is usually handled at intermediate level.

b. Wheel Rebuilding Station

This design concept is a somewhat more ambitious robotic system that performs the following functions automatically:

- Accept an aircraft wheel
- Deflate the tire
- Remove tire
- Inspect the tire

- Repair or replace tire
- Disassemble the wheel
- Inspect the brake mechanism
- Replace worn components
- Reassemble the wheel and brake mechanism
- Replace the tire
- Set beads
- Inflate to test pressure
- Re-inspect the tire
- Reduce pressure to working value
- Deliver the rebuilt wheel.

Such a system could require several tens of millions of dollars in development, and each individual station would cost millions. It would address primarily the problems of surge capacity and safety (tire explosion and asbestosis). The technical risks are higher than in rebuilding a turbine because of the large number of fasteners involved, some parts that are too large and heavy for a typical assembly robot to handle, and the mechanical complexity of the wheel/brake assembly. However, for the following reasons, the risks are not unreasonable:

- The components to be handled are all rigid and of predictable shape, except for the tire which is nearly so.
- None of the parts are extremely small.
- The smallest parts can be handled with commercial vibratory feeders and orienters.
- Nondestructive test methods exist for the inspection tasks (ultrasonics, 3-dimensional vision, holography, etc.).
- Semi-automatic bead breakers exist.

The primary technical risk lies in raising the performance of sensing, control, and effector technology to adequate levels. The primary need is for dexterous manipulation in the assembly and disassembly of the wheel/brake mechanism. The components have a wide range of size and weight from a bolt to a 50-pound tire carcass, necessitating co-ordination of different handling and manipulation mechanisms. The most difficult problem is probably the occasional need to machine out a damaged bolt from the brake mechanism. A skilled machinist may take hours to accomplish this, we were told. This would probably have to remain a manual operation.

c. Engine Rebuilding Center

One of the most difficult and important tasks in an IMF is the disassembly and reassembly of engines. The high cost of a ruined engine, and the danger of engine failure in flight make engine repair also one of the most critical maintenance tasks. Some of this work could be automated with existing robotic technology, but probably not enough to make it worthwhile. Advances in technology are required to make this application practical.

Generally speaking, there are three distinctly different types of activity involved in repairing a machine such as an engine. In order of increasing difficulty, they are :

- Disassembly of a clean, undamaged machine
- Assembly of the machine from clean, undamaged parts
- Disassembly of a damaged or dirty machine.

We omit the case of assembling the machine with dirty or damaged parts, since this will hopefully be an uncommon practice.

The ordering above may seem surprising. The reason for the ordering is that unpredictability makes a task more difficult. Disassembling a clean, undamaged machine is easiest because the position of every part in the machine can in principle be known quite precisely to start with. A robot requires little sensing, if any, to remove fasteners, grasp and remove components, etc. Parts removed can be placed anywhere that is convenient.

Assembling the same machine would be no more difficult than disassembling it, if it were economic to present every component to the robot in a precise, known position. In practice, this is usually prohibitively expensive because special tooling such as jigs, fixtures, part feeders, and so on must be specially built for each different part. Even then, there may be so many parts that there is no room for all the tooling around the robot. Then additional tooling such as conveyors must be built to bring the parts to the robot. Or, the robot must be made mobile so that it can go and get the parts it needs. A more

economic approach is to supply parts jumbled in bins or trays, and let the robot pick out the one it needs next. This is difficult because the part positions and orientations are now unpredictable (to arrange them neatly in the bin would require another person, special tooling, or other robots, which would also be expensive). So, the main difference between assembly and disassembly is the need for the robot to obtain individual components and orient them.

Damage and dirt introduce additional variability in a task that are difficult for a robot to deal with. Damage can make a part unrecognizable to the robot. Worse, it may make the part unsafe to use, but still recognizable, and the robot might install it. Dirt also makes parts difficult to recognize and handle. In addition, it can spread to other parts and to the robot itself. Dirt can get into a threaded hole, for example, making it impossible to put a bolt into it. It can get into the mechanisms of the robot, especially its hand, and jam it. The main problem with damaged and dirty parts is that they introduce the possibility of new failure modes of such variety that they are in principle impossible to predict and plan for. It is then, by definition, impossible to provide either tests for those failures or corrective actions.

In addition to damage and dirt, any flexible parts, such as wires, gaskets, and hoses, also cause problems because their shape and motion is usually unpredictable. Loose parts, or parts that become loose when other parts are removed also required special treatment.

Nevertheless, robotic technology offers the promise of a highly-automated engine repair facility. Most of the dirt would be removed with sprays first. The robot would do the bulk of the disassembly. Whenever it came to a part that was too damaged for it to deal with, a person would help it out. The person might remove the part himself, instruct the robot how to remove it, or operate the robot by remote control. One person might be able to look after several robots, for a consequent reduction in skill and manpower. The robot could carry out many cleaning, sorting, and inspection procedures on the individual

components that are now performed manually. It could discard and replace defective ones. Assembly could probably be completely automatic, if only clean, undamaged parts are used.

Naturally, if a robotic engine-repair facility like this could be put together, we would have the technology in hand to do much more than simply repair engines. In fact, industry around the world would be quite revolutionized by those technologies. This is, of course, why those technologies are topics of such vigorous research today here and abroad (especially in Japan).

The technical difficulties in developing such equipment should not be underestimated. Many robotic technologies would have to be considerably advanced, and many current problems in AI research would have to be solved. But there does not at present seem to be any reason to suppose that this is impossible. For example, experimental robots in various laboratories have already demonstrated rudimentary senses of vision and touch, picked parts out of bins, built wire harnesses, and assembled simple mechanical products.

All of the required technologies in fact exist today, although many of them are only in the "Model T" stage. They include all the AI technologies, as well as the following robotic ones:

- Smaller, lighter, stronger actuators
- Multiple-fingered, dexterous hands
- Tactile sensors
- 3D vision
- Faster manipulators with more joints
- Mobile robots
- Methods for co-ordinating activities of multiple robots
- Faster, more accurate joint servos capable of position, velocity, and force control
- Use of component shape descriptions stored in computer-aided design data bases
- Integration with management information systems.

Such tasks could be automated to a large extent with foreseeable improvements to present-day robotic technology. The main problem with today's robots is that they lack the dexterity required. The pacing technologies for this application include the following:

- Actuator mechanisms
- Mechanical transmissions
- End-effector (dexterous grippers)
- Force and torque sensing at the end-effector
- Finger-tip tactile sensing
- Vision (for location, identification, position, measurement, and inspection for integrity)
- Proximity measurement (independent of shape, material, or finish of sensed objects).

A robotic system that could disassemble and reassemble engines would be quite a large advance over any present robotic equipment, even in Japan. It would be extremely complex and expensive, and might require 100 man-years of R&D. It would, of course, be suitable for repairing many other kinds of equipment.

7. <u>IE -- Automatic Inspection Equipment</u>

An IMF often has a centralized nondestructive test (NDT) facility. The basic activities in such facilities could be automated. The most likely justification for doing so would probably be to provide surge capability if NDT specialists should be in short supply.

Three important types of NDT procedures performed in an IMF include the following:

- Detection of internal flaws using ultrasonics
- Detection of external cracks using magnetic particles
- General internal examination of objects using X-rays.

The most important conclusion that we drew from our study of these procedures is that they all rely on visual analysis to determine test results. Magnetic particle testing shows up surface cracks in a part as fine colored lines. Ultrasonic testers display an oscilloscope trace of

echoes from inside the part under test. X-rays, of course, produce extremely detailed images which require training to evaluate properly.

Automating NDT procedures therefore requires either (1) implementing a computer vision system that can analyze such visual patterns, or, (2) modify the NDT test equipment to produce its test results in a form that can be directly input to a computer.

Magnetic particle tests would seem to require looking at the parts. Ultrasonic data could be supplied to the computer as digitized reflected-energy data versus time. X-ray images could be acquired directly, without expensive X-ray film and time delays to develop it.

An important part of NDT procedures is handling the parts to be tested. Parts almost always have to be clean before they can be inspected. Bulk cleaning operations typically disorient parts. Often, different parts are mixed together in a batch for more efficient cleaning. To eliminate a manual sorting and orienting operation, it would be advantageous if the robot system can do it. The overall NDT task is then to singulate, identify, and orient parts, place them into an appropriate test fixture, operate the NDT equipment, and read the results. It will be difficult to make a robot system that can handle parts of any arbitrary shape, however. Much progress has been made in recent years on this problem, however.

We propose robotic NDT systems for each of the three methods mentioned above. These might all be incorporated into a single automated NDT facility. Each system would accept a bin of small parts, perhaps of different types, and would sort out the good parts from the defective ones.

a. Robotic Ultrasonic Inspection System

In this concept, a robot moves an ultrasonic probe over the surface of the part. Relatively straightforward robot control technology would be sufficient to accomplish this.

Several versions of this concept are possible. The simplest is a fixed, automatic installation in an NDT center. A long-armed teleoperated version might be useful for certain tests performed on parts in place on an aircraft, such as motor mounts, wing roots, and helicopter rotor blade attachments. Using it, the technician would not have to risk climbing around on the aircraft. An autonomous, mobile version of this robot could go to the aircraft and perform such tests by itself. That version would require a large development effort, however.

One benefit of such systems could be increased aircraft safety, by making possible more tests with less manpower.

b. Filmless X-ray Inspection System

This system would use electronic means to capture X-ray data instead of film. Several technologies exist for this purpose (X-ray-sensitive solid-state imaging chips, scintillometers, "baggage X-ray" machines, optical imaging of a fluoroscope screen, etc.). A robot arm would present parts to the X-ray equipment, perhaps in its own gripper, since it would not be damaged by the radiation. A computer would then analyze the X-ray data in any of several different ways in real time, without having to wait for chemical development of a film.

The computer might use sophisticated AI-style image analysis routines to evaluate the data as a high-resolution gray-scale image. Or, it might just compare the X-ray data point-for-point with a stored copy of a scan of a good part. Which methods are applicable will depend upon the objects and what kind of defects are important. The more difficult inspection procedures would require some means for the NDT facility supervisor to tell the system what to look for.

c. Robotic Magnetic Particle Inspection Station

In this concept, one or two robot arms would coat metal parts with a liquid containing magnetic particles. It would then magnetize them, and visually inspect the surface of the parts for cracks. These will show up as concentrations of the particles, which, being brightly colored or fluorescent, create narrow lines on the surface of the part.

Paint and dirt must be removed from the parts before testing, so that the particles can reach any cracks. This involves dipping and soaking the parts in tanks of various liquids. Some parts may have to be brushed or otherwise forcibly cleaned off. That would greatly complicate the manipulator-control problem.

Knowing how to clean and prepare different kinds of parts, and how to magnetize them requires some skill and training. This suggests that AI expert systems methods will be needed. Finding the cracks shown up by the particles could be a difficult computer vision problem, especially if the system must be able to handle parts of any shape.

8. FR — Fabrication Robots

A number of fabrication operations are commonly performed at an IMF, such as the following:

- Bending tubes
- Making hoses
- Making wire harnesses
- Drilling hole patterns in aircraft skins
- Arc welding, both in the shop and in an aircraft
- Sheet metal forming.

If the work load is heavy enough, some of these jobs may be worth automating. Here, we propose three systems—for tube bending, drilling precise hole patterns in sheet metal, and for arc welding.

a. Automatic Tube Bending System

This concept is the use of automatic equipment to bend tubing of various lengths and diameters to make replacements for damaged tubing in an aircraft. The Vector-1 measuring arm* can measure the shape of a piece of bent tubing precisely and place this information on a magnetic computer tape. The tape can then control an automatic tube bender to make exact copies from stock at any time. The original tube need not be retained as a model.

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* Eaton-Leonard, Incorporated, Carlsbad, California.

This is an application of the simplest kind of robotics technology. In fact, a robot-like manipulator arm is used as a measuring device to determine the shape of the original tube. It is unpowered, and a skilled operator grasps its "hand" and places it a various points along the tube to determine the tube's shape.

This is the lowest-risk of all the AI/robotic design concepts in this report, because the commercial equipment already exists and is used by aircraft manufacturers.

b. Templateless Drilling Robot

This design concept is a robot for drilling precise patterns of holes in aircraft skin panels without the need to make full-scale templates. The benefits include increased productivity, as well as eliminating the labor and material costs that go into the templates. The risk is only moderate, because the U.S. Air Force is developing robotic technology to allow a commercial robot manipulator to do just this. The concept is based on the use of accurate external sensors to continually measure and correct errors in the actual position and orientation of the drill. This research is part of the USAF's Integrated Computer-Aided Manufacturing (ICAM) project.

The ICAM project intends to program the robot for this task directly from a computer-aided design data base for the aircraft. But the repairs and modifications made to an aircraft during its service life can quickly make the manufacturer's original CAD data obsolete. So, for maintenance applications a rapid training procedure would probably be more practical than fully-automatic operation.

Consider replacing a fuselage panel, for example. One has to drill rivet holes in the newly-formed panel to match the existing holes in the airframe. The maintenance technician could use a teleoperator/remote control to move a robot arm near to each of the holes on the airframe. A sensor in the hand would record the precise hole position. The drilling robot (which might be the same one used to find the holes) could then use this information to drill the required holes in the panel.

c. Robotic Arc Welding Station

This concept is a robotic arc welder. Any of several commercial welding robots could be used as is for some intermediate maintenance welding, if the volume of work is large enough to justify it. Potential benefits include higher productivity, increased uniformity, and possibly increased safety. Technological risk is almost as low as for the tube bender, and development time could be negligible.

The main risk in this design concept is justifying the use of a robot. It has to be trained for each new job, and it is out of service during that time. If the training is not perfect, additional time and material is lost in correcting it. The trainer has to be a skilled welder. To make good use of his time, he should have to supervise several robots working simultaneously.

A robot welder will be easiest to justify if it will be welding many identical parts continuously. In fact, in such situations a robot can keep the arc burning so much more of the time compared to a human welder that it may need a welding power supply with a 50% higher rating!

Justification will probably be difficult because much IMF welding is nonrepetitive. Some typical jobs are constructing special maintenance equipment for use by the IMF, and repairing broken parts.

IV COST-BENEFIT METHODOLOGY

A. Introduction

The objective of the research described in this chapter was to establish criteria for assessing the cost-benefit tradeoffs with respect to the future implementation of existing and projected artificial intelligence (AI) and robotics techniques into the field of Navy aircraft maintenance. The criteria shall be amenable to quantification through the establishment of appropriate measures of effectiveness for use with resource allocation techniques.

The cost-benefit factors and the associated measures of effectiveness established are described in Section B. The basic structure of the proposed computer model to be used for cost-benefit analyses is described in Section C. A sample demonstration of the use of the Cost-Benefit Model for a hypothetical AI/robotic application is presented in Section D. Appendix B to this report presents a summmary description of a utility structured data base design for representing manpower requirements.

B. Cost-Benefit Factors

1. General

The underlying objective of Navy R&D is to develop new techniques, procedures and equipment that will enhance Navy readiness at reduced cost and manpower. In general terms then, the establishment of cost-benefit criteria must encompass the three factors: readiness, cost and manpower. The following sections address these factors in turn and identify associated measures of effectiveness that can be used to evaluate the cost-benefit tradeoffs of alternate R&D projects and programs related to Navy aircraft maintenance.

2. Readiness

Readiness has been defined in a previous SRI report[1*] as "the degree to which an organizational entity is capable of performing, to its maximum potential, the missions for which it is organized, during a normal operating cycle." This definition is, of course, quite general in nature and must be appropriately modified in both structure and terminology when addressing a particular problem within a specified mission area.

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* References are listed at the end of this report

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For Navy aviation, at the wing or squadron level, readiness primarily refers to the expected numbers of aircraft that are operationally ready at any given time during a specific deployment period. These expected values are directly related to the operational availability of the individual aircraft, the availability of qualified aircrews to properly operate the aircraft, and the availability of sufficient amounts of fuel and ordnance to meet mission requirements over the deployment period. The latter two factors are not functions of aircraft maintenance, but the first factor is highly dependent on maintenance efficiency.

The operational availability of an aircraft can be defined as the probability that the aircraft is fully operational at any given time during the deployment. In its simplest form, operational availability, denoted by OA, can be represented as follows:

$$OA = \frac{TUT}{TUT + TDT} \tag{1}$$

Where TUT is the total up-time and TDT is the total down-time for an airccraft over the period of deployment. OA is, of course, the unity complement of the NOR (not-operationally-ready) rate, which is used more frequently in Navy parlance. The NOR rate can be broken down into two components: NORM (NOR-Maintenance) rate and NORS (NOR-Supply) rate. Although this factorization is convenient in assessing the causative factors contributing to the NOR rate, these factors are not additive and also are not necessarily independent. That is, a decrease in the NORM rate could be somewhat offset by an induced increase in the NORS rate, e.g., if the spare part inventory is not sufficient to support the resulting increase in maintenance activity. Thus, in evaluating the effects on readiness of postulated maintenance techniques, procedures, and equipment, the NOR rate should be the guiding measure of effectiveness.

In terms of Eq. (1), the NOR rate can be represented as follows:

$$\text{NOR rate} = \frac{TDT}{TUT + TDT} \tag{2}$$

One problem with using the NOR rate, as represented above, is the need to specify an appropriate time period as a basis for the NOR rate computation (note that the denominator of Eq. 2 represents this time period). This basic

time period could be periodic, say weekly or monthly, or it could be the total period of deployment of the aircraft's squadron, which would be a variable time period dependent on the nature of the squadron's deployment. The time period could also be an expanding time period, reflecting the elapsed deployment time for a squadron during a specified deployment period.

One convenient way to eliminate the selection of a specific time period is to consider the aircraft operability status as a two-state stochastic process, with the two states being "up" or "down". Upon deployment, the aircraft will be up for a random period of T_{U1} time units at which time a malfunction occurs, and then the aircraft will be down for a random period of T_{D1} time units. The aircraft then will be up for a random period of T_{D2} time units, and so on. At the end of the N^{th} such up-down cycle, Eq. (2) can be rewritten as follows:

$$\text{NOR rate} = \frac{\sum_{i=1}^{N} T_{Di}}{\sum_{i=1}^{N} T_{Ui} + \sum_{i=1}^{N} T_{Di}} \tag{3}$$

If we divide numerator and denominator by N, then Eq. (3) becomes

$$\text{NOR rate} = \frac{\text{MDT}}{\text{MUT} + \text{MDT}} \tag{4}$$

where MDT is the mean down-time and MUT is the mean up-time. This representation of the NOR rate eliminates the need for specifying an explicit measurement time period and is also very convenient for use in a predictive mode, such as estimating the effects on the NOR rate of postulated changes in maintenance techniques, procedures, and equipment.

Another problem of using the NOR rate as a measure of effectiveness for aircraft maintenance is that this measure depends not only on maintenance efficiency, but also on the aircraft's operational profile, or more succinctly, the frequency of aircraft malfunctions. That is, the up-time components of Eq. (2), (3) or (4) are measured in calendar hours, as opposed to flying hours, and as such are highly dependent on the aircraft sortie rate. If the operational profile remains relatively stable during the period of deployment, then this up-time component will be relatively constant and so the NOR rate can provide a good measure to evaluate the effects of changes in the

maintenance program. However, if this profile is variable, and even worse, unpredictable, then the NOR rate loses much of its usefulness as a measure of maintenance efficiency. Also, although in an indirect manner, the down-time components of the referenced equations also depend on the operational profile. That is, higher sortie rates induce higher failure rates (in calendar time) which impose a heavier burden on the maintenance components, which in turn lead to longer single aircraft down-times due to an overloading of the maintenance components.

In a predictive mode, the aircraft operational profile can be assumed constant, based on a representative scenario (or set of scenarios), so that this problem can be alleviated. Under this assumption, the mean up-time can be assumed as a constant and so the NOR rate is then strictly a function of the mean down-time. Since the mean down-time, often referred to as the maintenance turnaround time, is a commonly used measure of the responsiveness of the maintenance activities, then readiness can be directly related to maintenance responsiveness through consideration of the NOR rate, or more specifically, the maintenance turnaround time.

Within the context of the above discussion, the maintenance turnaround time then will be used as the readiness measure for evaluating the cost-benefit tradeoffs of possible implementation of AI/robotic techniques and procedures directed to the enhancement of maintenance system efficiency.

3. Cost

The cost factor must consider all cost elements that would be included in a Life Cycle Cost (LCC) analysis. These cost elements can be grouped into two major categories: Capital Investment Costs and Operations and Maintenance, Navy (O&MN) Costs. The Capital Investment Costs refer to all one-time costs incurred in fielding a system or implementing an operational concept, ranging from initial R&D costs on up through the actual establishment of the system or concept aboard ship or at a Navy installation. The O&MN costs refer to the annual recurring costs associated with operating and maintaining the system during its intended useful lifetime. The partcular cost elements included in the above categories are as listed below:*

* The cost element categorization is adopted, for the most part, from the NAVFAC Economic Analysis Handbook[2].

Capital Investment Costs

- Research & Development - all costs incurred for research and development, from basic research through exploratory and advanced development to engineering development and testing.
- Facility Investment Costs - all costs associated with the acquisition of equipment and real property; rehabilitation or modification of existing facilities; operations and maintenance start-up costs; one-time personnel costs (recruitment, separation, relocation, training, etc.); and other nonrecurring costs and services.
- Working Capital Changes - costs, both positive and negative, associated with changes in assets on hand or on order, such as spare parts and supplies in inventory or in the pipeline.
- Value of Existing Assets Replaced - cost savings incurred through the release of existing assets, provided these assets can be put to alternative use.
- Future Terminal Value - the present value of the estimated value of the proposed investment at the end of its estimated useful lifetime (usuallly negligible).

Operations and Maintenance, Navy (O&MN) Costs

- Personnel Costs - all costs of civilian and military personnel, including salaries, employee benefits, subsistance and travel costs, replacement and rotation costs, training costs, and other recurring costs.
- Operating Costs - all costs incurred for materials, supplies, handling, storage, utility services, and other recurring costs associated with the operation of the system.
- Maintenance & Repair Costs - all costs associated with the maintenance and repair of equipment and facilities associated with the system.
- Overhead - the costs of accounting, legal, local procurement, medical services, receipt, storage and issue of base supplies, police, fire, and other services.

The cost elements included in the above categories, although not exhaustive, are quite extensive and in most cases, many of the identified cost

elements will either not be applicable or else will be relatively insignificant in the long run. Thus, in determining the life cycle costs associated with the implementation of a particular aircraft maintenance system or concept, care should be exercised to identify those cost elements that will be significant in the ensuing cost-benefit analysis.

In performing a cost-benefit analysis, all cost elements must be discounted to their present value, taking into account inflation, interest, and other factors that generate disparities between the values of future and present expenditures. Although Capital Investment and O&MN costs could be combined into a single cost factor, it is preferable to keep them separated since the necessary funds are obtained from different government accounting sources. When considering equipment and procedural modifications to systems already deployed, many of the system cost elements will not be affected by such modifications and hence need not be considered per se. That is, one is interested more in the net changes to the cost factors than in the total life cycle cost.

Within the context of the above discussion, the net changes in Capital Investment Costs and O&MN Costs will be used as the cost measures for evaluating the cost-benefit tradeoffs of possible implementation of AI/robotic techniques and procedures directed to the enhancement of maintenance system efficiency.

4. Manpower

The manpower factor must consider not only the numbers of personnel required, but also the required distribution of skill levels within the manning structure. Since the skill level distribution is spread over a wide variety of components (officer designators and pay grades, EP ratings and pay grades, and civilian occupational codes and pay scales), it is necessary for a cost benefit analysis to represent this distribution in terms of much more aggregated components. One approach that proved useful in a previous SRI analysis[3] was to establish a utility data base structure that consisted of 18 utility pay grades, 7 utility skill groups, and a utility value for each pay grade/skill group combination. Each officer, EP, and civilian pay grade was appropriately equivalenced to a utility pay grade, and each officer designator, EP rating, and civilian occupational code was assigned to one of the seven utility skill groups. Normalized utility values were then

established for each skill group level as a function of the utility pay grades. With this data base structure, each authorized Navy billet could be associated with a representative utility value that considers both the skill level and pay grade of that billet, regardless of whether it is an officer, EP, or civilian billet. A summary description of this data base structure is presented as Appendix B to this report.

The use of this utility base structure provides a convenient vehicle for aggregating the various manpower requirements for evaluating the cost-benefit tradeoffs of alternative R&D projects and programs related to Navy aircraft maintenance. At the most aggregate level, the manpower requirement of the maintenance components or activities associated with implementation of a particular aircraft maintenance system or concept can be specified simply as the total number of personnel required and the average utility per person. A reduction in either number then would represent a reduction in the overall manpower requirements. In some cases, it may be advantageous to consider a somewhat lesser level of aggregation by specifying the numbers of officers, EPs, and civilians and the associated average utility per person for each of these personnel categories. For the purposes of this analysis, the higher level of aggregation will be adopted and thus the manpower factor in the cost-benefit analysis will be represented by the total number of personnel and the average utility per person for the required maintenance components or activities.

C. Cost-Benefit Model

1. Method of Approach

The field of feasible applications of AI/robotics is still in its infancy and more basic research and development is required to foster its growth to the point that prospective applications will have a considerable impact on Navy aircraft maintenance, especially at the organizational and intermediate levels. In most cases, a practical application of AI/robotics will require technological breakthroughs in two or more research areas. When taken alone, these advances may not induce significant benefits, but when combined, the synergistic effects of their joint occurrence may prove extremely beneficial. These factors were thus given due consideration in the development of a model for evaluating the cost-benefit tradeoffs of possible

implementation of AI/robotics techniques and procedures directed to the enhancement of Navy aircraft maintenance system efficiency.

The approach used in developing the model considered three distinct time phases in the life cycle of a proposed system: Research and Development (R&D) Phase, Manufacturing and Installation (M&I) Phase, and Operations and Maintenance (O&M) Phase. The R&D Phase addresses the research and development projects that are associated with specific research areas directed toward a perceptual AI/robotic application to Navy aircraft maintenance. For this phase, the model individually considers each R&D project and establishes a project's total R&D costs and the probability that the project will come to a successful conclusion, beginning with basic research, through exploratory and advanced development, and culminating with engineering development. The model also determines the expected investment loss, should a project be cancelled for lack of realizing its planned potential during any R&D phase.

The M&I Phase addresses specific combinations of successful R&D projects that, when merged, would result in useful AI/robotic applications to Navy aircraft maintenance. For each such combination, the model computes the overall manufacturing and installation costs for the associated application. This is accomplished by first identifying the affected work centers at the organizational, intermediate and depot maintenance levels, and then by determining the total number of 'systems' (equipment, procedures, and/or techniques) that must be implemented considering the Navy-wide distribution of maintenance activities. The model also computes the total R&D investment cost for each application (combination of successful research projects), which includes the R&Ds costs associated with the successful research projects, as well as the expected investment losses associated with the unsuccessful and unusable R&D projects. The model than determines the total investment cost for an application by combining the R&D costs with the M&I costs.

The O&M Phase addresses the operations and maintenance of the new systems. For this phase, the model computes the total differential O&M costs to be realized through the implementation of the new systems, as well as the differential personnel and response time benefit factors.

The three phases of the model are described in detail in the following subsections.

2. Research and Development Phase

The R&D Phase assumes that a large-scale R&D program directed to a major AI/robotics application to Navy aircraft maintenance is to be implemented. This program consists of a number of independent R&D projects directed toward advancing the state-of-the-art within distinct areas of AI/robotics technology. If the objectives of all of the research projects are realized, then the intended AI/robotic application can be implemented, resulting in a maximum payoff with regards to cost-benefit factors. However, the research program is designed so that some cost-benefit payoffs can be realized if only selected subsets of the projects reach fruition. The R&D Phase of the model addresses only the individual R&D projects. The combinations of successful projects are then merged together in the M&I Phase.

For each R&D project in the research program, the R&D Phase of the model establishes the probability of success, the total R&D costs, the expected completion dates, and the expected investment loss should the project be unsuccessful or not used in an ensuing AI/robotic application. Each R&D project is assumed to consist of four phases: basic research, exploratory development, advanced development, and engineering development. At the end of each phase, the project will either move into the next phase or else be shelved. If it is shelved at the end of any phase, then the R&D costs incurred to that time will be considered as investment losses. If the project proceeds successfully through all four phases, then the project will be deemed a success and the R&D costs incurred will be included in the total R&D costs for an application if the project is included in the associated combination of projects. If the project is not included in the associated combination of projects, then the R&D costs of the project, though successful, will be considered as an investment loss since the utility of the project results was dependent on the success of an unsuccessful companion R&D project.

The model inputs required for the R&D Phase are as follows:

N_{RD} = total number of R&D projects in research program

i = R&D project number ($i=1, \ldots, N_{RD}$)

$C_{BR}(i)$ = expected cost of basic research for project i

$C_{EXD}(i)$ = expected cost of exploratory development for project i

$C_{AD}(i)$ = expected cost of advanced development for project i

$C_{EGD}(i)$ = expected cost of engineering development for project i

$P_{BR}(i)$ = probability that basic research phase is successful for project i

$P_{EXD}(i)$ = probability that exploratory development phase is successful for project i

$P_{AD}(i)$ = probability that advanced development phase is successful for project i

$P_{EGD}(i)$ = probability that engineering development phase is successful for project i

$T_{SU}(i)$ = expected start-up time for project i

$T_{BR}(i)$ = expected duration of basic research phase for project i

$T_{EXD}(i)$ = expected duration of exploratory development phase for project i

$T_{AD}(i)$ = expected duration of advanced development phase for project i

$T_{EGD}(i)$ = expected duration of engineering development phase for project i.

If, for a specific R&D project, one or more R&D phases will not be required, then the cost and time inputs for that phase would be zero and the probability of success would be unity.

The major outputs of the R&D Phase are as follows:

$C_{RD}(i)$ = total R&D costs for project i, given that it is successful and used in an implemented application

$P_S(i)$ = probability that project is successful

$T_{RD}(i)$ = expected time of completion of R&D for project i, given that it is successful

$L_I(i)$ = expected investment loss, given that the project is unsuccessful or not used in an implemented application

These outputs are computed in accordance with the following equations:

$$C_{RD}(i) = C_{BR}(i) + C_{EXD}(i) + C_{AD}(i) + C_{EGD}(i) \tag{1}$$

$$P_S(i) = P_{BR}(i) \cdot P_{EXP}(i) \cdot P_{AD}(i) \cdot P_{EGD}(i) \tag{2}$$

$$T_{RD}(i) = T_{SU}(i) + T_{BR}(i) + T_{EXP}(i) + T_{AD}(i) + T_{EGD}(i) \tag{3}$$

$$\begin{aligned} L_I(i) = {} & (1-P_{BR}(i)) \cdot C_{BR}(i) + P_{BR}(i) \cdot (1-P_{EXP}(i)) \cdot (C_{BR}Ii) \\ & + C_{EXP}(i)) + P_{BR}(i) \cdot P_{EXP}(i) \cdot (1-P_{AD}(i)(C_{BR}(i) + \\ & C_{EXP}(i) + C_{AD}(i)) + P_{BR}(i) \cdot P_{EXP}(i) \cdot P_{AD}(i) \cdot (1-P_{EGD}(i)) \cdot \\ & C_{RD}(i) + P_S(i) \cdot C_{RD}(i) \end{aligned} \tag{4}$$

The model computes the values of these outputs and then stores them for use in the M&I Phase of the model. The model also prints out an R&D Summary Table for each project. This table includes the following output data for each R&D phase of a project:

- duration time
- date of implementation
- date of completion
- probability of success
- R&D cost
- probability of termination
- expected investment loss.

3. Manufacturing and Installation Phase

The M&I Phase of the model addresses specific combinations of R&D projects that would result in a feasible application of AI/robotics to Navy aircraft maintenance. Each project combination addressed assumes that all other R&D projects either were unsuccessful or not usable because of a dependency on an unsuccessful companion R&D project. (If other R&D projects were useful, then they would be included in a larger combination of R&D projects). For each such combination, the M&I Phase establishes the total R&D costs associated with the projects contained in the combination, the expected investment losses associated with the projects not in the combination, and the manufacturing and installation costs associated with the full implementation of the AI/robotic systems throughout the Navy aircraft maintenance community. The model then combines these investment costs to determine the total investment cost associated with this AI/robotic application. The model also determines the time at which the application has been fully implemented and becomes operational on a Navy-wide basis.

The model inputs for the M&I phase are as follow:

N_{PC} = total number of project combinations considered

j = project combination number ($j=1,...N_{PC}$)

$NP(j)$ = number of R&D projects in project combination j

$PN(i,j)$ = R&D project number for project i in project combination $j(i=1, ..., NP(j))$

N_{OM} = number of organizational maintenance (OM) components within the Navy

N_{IM} = number of intermediate maintenance (IM) components within the Navy

N_{DM} = number of depot maintenance (DM) components within the Navy

$NWCT_{OM}(j)$ = number of work center types at the organizational maintenance level affected by project combination j

$NWCT_{IM}(j)$ = number of work center types at the intermediate maintenance level affected by project combination j

$NWCT_{DM}(j)$ = number of work center types at the depot maintenance level affected by project combination j

$NWC_{OM}(j,k)$ = number of work centers of type k for project combination j at an organizational maintenance component (k=1, ... $NWCT_{OM}(j)$)

$NWC_{IM}(j,k)$ = number of work centers of type k for project combination j at an intermediate maintenance component (k=1, ..., $NWCT_{IM}(j)$)

$NWC_{DM}(j,k)$ = number of work centers of type k for project combination j at a depot maintenance component (k=1, ..., $NWCT_{DM}(j)$)

$NS_{OM}(j,k)$ = number of systems required at a work center of type k for project combination j at an organizational maintenance component (k=1, ..., $NWCT_{OM}(j)$)

$NS_{IM}(j,k)$ = number of systems required at a work center of type k for project combination j at an intermediate maintenance component (k=1, ..., $NWCT_{IM}(j)$)

$NS_{DM}(j,k)$ = number of systems required at a work center of type k for project combination j at a depot maintenance component (k=1, ..., $NWCT_{DM}(j)$)

$C_{MAN}(j)$ = manufacturing cost per system for project combination j

$C_{INS}(j)$ = installation cost per system for project combination j

$T_{MI}(j)$ = expected duration for manufacturing and installation of systems for project combination j.

The major outputs of the M&I Phase are as follows:

$C_{TRD}(j)$ = total R&D cost for R&D projects included in project combination j

$C_{IL}(j)$ = total expected investment loss for R&D projects not included in project combination j

$C_{MI}(j)$ = total manufacturing and installation cost for project combination j

$C_{INV}(j)$ = total capital investment cost for project combination j

$T_{IMP}(j)$ = time of full implementation of systems for project combination j.

Before proceeding to the computation of the major outputs of the M&I Phase, the following auxiliary computation is performed:

$$
\begin{aligned}
NS_{TOT}(j) = {} & NOM \cdot \sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k) \cdot NS_{OM}(j,k) \\
& + NIM \cdot \sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k) \cdot NS_{IM}(j,k) \\
& + NDM \cdot \sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k) \cdot NS_{DM}(j,k)
\end{aligned}
\tag{5}
$$

where $NS_{TOT}(j)$ is the total number of systems to be installed for project combination j.

The major outputs for this phase are computed in accordance with the following equations

$$C_{TRD}(j) = \sum_{i=1}^{NP(j)} C_{RD}(PN(i,j)) \tag{6}$$

$$C_{IL}(j) = \sum_{\substack{m=1 \\ m \neq PN(i,j)}}^{N_{RD}} L_I(m) \tag{7}$$

$$C_{MI} = NS_{TOT}(j) \cdot (C_{MAN}(j) + C_{INS}(j)) \tag{8}$$

$$C_{INV}(j) = C_{TRD}(j) + C_{IL}(j) + C_{MI}(j) \tag{9}$$

$$T_{IMP}(j) = T_{MI}(j) + \max_{m = PN(i,j)} \left| T_C(m) \right| \tag{10}$$

4. Operations and Maintenance Phase

The O&M Phase of the model addresses the operation and maintenance of the implemented systems for each AI/robotic application represented by a specific R&D project combination. For each such combination, the O&M Phase

establishes the differential cost-benefit factors between the present mode of operations and that which would be practiced on full implementation of the new systems. The cost-benefit factors obtained during the phase are the differential annual O&MN costs, the differential average turnaround time (mean response time), the differential number of personnel required, and the differential average utility per person for the set of work centers affected by the implementation of the application. The computations performed during this phase are divided into three sections: personnel, O&MN costs, and turnaround time.

a. Personnel Section

The model inputs for the personnel section of the computations are as follows, where j denotes the project combination number ($j=1, \ldots, N_{PC}$), m denotes the maintenance level (m=OM, IM, DM), k denotes the work center type ($k=1, \ldots, NWCT_m(j)$) and a personnel category is defined as a utility pay grade/utility skill group combination (see Appendix B):

$NPC_{OLD}(j,m,k)$ = number of different personnel categories represented in this work center type under present system.

$NPC_{NEW}(j,m,k)$ = number of different personnel categories represented in this work center type under new system.

$UPG_{OLD}(j,m,k,p)$ = utility pay grade associated with personnel category p for this work center type under present system ($p=1, \ldots, NPC_{OLD}(j,m,k)$).

$UPG_{NEW}(j,m,k,p)$ = utility pay grade associated with personnel category p for this work center type under new system ($p=1, \ldots, NPC_{NEW}(j,m,k)$).

$USG_{OLD}(j,m,k,p)$ = utility skill group associated with personnel category p for this work center type under present system ($p=1, \ldots, NPC_{OLD}(j,m,k)$).

$USG_{NEW}(j,m,k,p)$ = utility skill group associated with personnel category p for this work center type under new system ($p=1, \ldots, NPC_{NEW}(j,m,k)$).

$P_{OLD}(j,m,k,p)$ = number of personnel of category p in this work center type under present system ($p=1, \ldots, NPC_{OLD}(j,m,k)$)

$P_{NEW}(j,m,k,p)$ = number of personnel of category p in this work center type under new system ($p=1, \ldots, NPC_{NEW}(j,m,k)$).

The first set of computations are directed to the accumulation of the personnel cost-benefit factors at the work center level. These factors are as follows:

$NP_{OLD}(j,m,k)$ = number of personnel in this work center type under present system

$NP_{NEW}(j,m,k)$ = number of personnel in this work center type under new system

$U_{OLD}(j,m,k)$ = total utility associated with personnel in this work center type under present system

$U_{NEW}(j,m,k)$ = total utility associated with personnel in this work center type under new system

$PC_{OLD}(j,m,k)$ = total monthly billet costs for personnel in this work center type under present system

$PC_{NEW}(j,m,k)$ = total monthly billet costs for personnel in this work center type under new system

These factors are computed as follows:

$$NP_{OLD}(j,m,k) = \sum_{p=1}^{NPC_{OLD}(j,m,k)} P_{OLD}(j,m,k,p) \tag{11}$$

$$NP_{NEW}(j,m,k) = \sum_{p=1}^{NPC_{NEW}(j,m,k)} P_{NEW}(j,m,k,p) \tag{12}$$

$$U_{OLD}(j,m,k) = \sum_{p=1}^{NPC_{OLD}(j,m,k)} P_{OLD}(j,m,k,p) \cdot U(UPG_{OLD}(j,m,k,p),\ USG_{OLD}(j,m,k,p)) \tag{13}$$

$$U_{NEW}(j,m,k) = \sum_{p=1}^{NPC_{NEW}(j,m,k)} P_{NEW}(j,m,k,p) \cdot U(UPG_{NEW}(j,m,k,p),\ USG_{NEW}(j,m,k,p)) \tag{14}$$

$$PC_{OLD}(j,m,k) = \sum_{p=1}^{NPC_{OLD}(j,m,k)} P_{OLD}(j,m,k,p) \cdot C(UPG_{OLD}(j,m,k,p),\ USG_{OLD}(j,m,k,p)) \tag{15}$$

$$PC_{NEW}(j,m,k) = \sum_{p=1}^{NPC_{NEW}(j,m,k)} P_{NEW}(j,m,k,p) \cdot C(UPG_{NEW}(j,m,k,p),\ USG_{NEW}(j,m,k,p)) \tag{16}$$

where the functions U(UPG,USG) and C(UPG,USG) are respectively the utility and billet cost values for the various utility pay grades and skill groups as presented in Tables B-4 and B-5 of Appendix B.

These work center outputs are then spread out over the Navy-wide distribution of maintenance components to establish the following totals:

$NPT_{OLD}(j)$ = total number of personnel associated with work centers affected by project combination j under present system

$NPT_{NEW}(j)$ = total number of personnel associated with work centers affected by project combination j under new system

$UT_{OLD}(j)$ = total utility associated with personnel in work centers affected by project combination j under present system

$UT_{NEW}(j)$ = total utility associated with personnel in work centers affected by project combination j under new system.

$PCT_{OLD}(j)$ = total monthly billet costs for personnel in work centers affected by project combination j under present system

$PCT_{NEW}(j)$ = total monthly billet costs for personnel in work centers affected by project combination j under new system.

These totals are computed as follows:

$$\begin{aligned} NPT_{OLD}(j) &= N_{OM} \cdot \sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k) \cdot NP_{OLD}(j,OM,k) \\ &+ N_{IM} \cdot \sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k) \cdot NP_{OLD}(j,IM,k) \\ &+ N_{DM} \cdot \sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k) \cdot NP_{OLD}(j,DM,k) \end{aligned} \tag{17}$$

$$\begin{aligned} NPT_{NEW}(j) &= N_{OM} \cdot \sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k) \cdot NP_{NEW}(j,OM,k) \\ &+ N_{IM} \cdot \sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k) \cdot NP_{NEW}(j,IM,k) \\ &+ N_{DM} \cdot \sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k) \cdot NP_{NEW}(j,DM,k) \end{aligned} \tag{18}$$

$$
\begin{aligned}
UT_{OLD}(j) = {} & N_{OM} \cdot \sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k) \cdot U_{OLD}(j,OM,k) \\
& + N_{IM} \cdot \sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k) \cdot U_{OLD}(j,IM,k) \\
& + N_{DM} \cdot \sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k) \cdot U_{OLD}(j,DM,k)
\end{aligned}
\tag{19}
$$

$$
\begin{aligned}
UT_{NEW}(j) = {} & N_{OM} \sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k) \quad U_{NEW}(j,OM,k) \\
& + N_{IM} \cdot \sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k) \cdot U_{NEW}(j,IM,k) \\
& + N_{DM} \cdot \sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k) \cdot U_{NEW}(j,DM,k)
\end{aligned}
\tag{20}
$$

$$
\begin{aligned}
PCT_{OLD}(j) = {} & N_{OM} \cdot \sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k) \cdot PC_{OLD}(j,OM,k) \\
& + N_{IM} \cdot \sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k) \cdot PC_{OLD}(j,IM,k) \\
& + N_{DM} \cdot \sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k) \cdot PC_{OLD}(j,DM,k)
\end{aligned}
\tag{21}
$$

$$
\begin{aligned}
PCT_{NEW}(j) = {} & N_{OM} \cdot \sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k) \cdot PC_{NEW}(j,OM,k) \\
& + N_{IM} \cdot \sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k) \cdot PC_{NEW}(j,IM,k) \\
& + N_{DM} \cdot \sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k) \cdot PC_{NEW}(j,DM,K)
\end{aligned}
\tag{22}
$$

These Navy-wide totals are then used to compute the differential personnel outputs which are:

$\Delta NP(j)$ = differential number of personnel for project combination j

$\Delta AU(j)$ = differential average utility per person for work centers affected by project combination j

$\Delta PC(j)$ = differential personnel monthly billet costs for project combination j.

These outputs are computed as follows:

$$\Delta NP(j) = NPT_{NEW}(j) - NPT_{OLD}(j) \tag{23}$$

$$\Delta AU(j) = \frac{UT_{NEW}(j)}{NPT_{NEW}(j)} - \frac{UT_{OLD}(j)}{NPT_{OLD}(j)} \tag{24}$$

$$\Delta PC(j) = PCT_{NEW}(j) - PCT_{OLD}(j) \tag{25}$$

The first two outputs are primary cost-benefit factors and are printed out for each project combination in the Project Combination Summary Output Table. The third output is used in the O&MN costs section to determine differential annual O&MN costs.

b. <u>O&M Costs Section</u>

The model inputs for the O&MN Costs section of the computations are as follows, where j denotes the project combination number (j=1, ..., N_{PC}), m denotes the maintenance level (m=OM, IM, DM) and k denotes the work center type (k=1, ..., $NWCT_m(j)$):

$OC_{OLD}(j,m,k)$ = monthly operating cost for this work center type under present system

$OC_{NEW}(j,m,k)$ = monthly operating cost for this work center type under new system

$RMC_{OLD}(j,m,k)$ = monthly repair and maintenance cost for this work center type under present system

$RMC_{NEW}(j,m,k)$ = monthly overhead cost for this work center type under new system

$OHC_{OLD}(j,m,k)$ = monthly overhead cost for this work center type under present system

$OHC_{NEW}(j,m,k)$ = monthly overhead cost for this work center type under new system

The first computations are directed to the determination of the differential monthly costs for all the work categories of operations, repair and maintenance, and overhead, denoted respectively by $\Delta OC(j)$, $\Delta RMC(j)$ and $\Delta OHC(j)$. These computations are performed in accordance with the following equations:

$$\begin{aligned}\Delta OC(j) = {} & N_{OM}\cdot\sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k)\cdot\left[OC_{NEW}(j,OM,k) - OC_{OLD}(j,OM,k)\right]\\ & + N_{IM}\cdot\sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k)\cdot\left[OC_{NEW}(j,IM,k) - OC_{OLD}(j,IM,k)\right]\\ & + N_{DM}\cdot\sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k)\cdot\left[OC_{NEW}(j,DM,k) - OC_{OLD}(j,DM,k)\right]\end{aligned} \tag{26}$$

$$\begin{aligned}\Delta RMC(j) = {} & N_{OM}\cdot\sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k)\cdot\left[RMC_{NEW}(j,OM,k) - RMC_{OLD}(j,OM,k)\right]\\ & + N_{IM}\cdot\sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k)\cdot\left[RMC_{NEW}(j,IM,k) - RMC_{OLD}(j,IM,k)\right]\\ & + N_{DM}\cdot\sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k)\cdot\left[RMC_{NEW}(j,DM,k) - RMC_{OLD}(j,DM,k)\right]\end{aligned} \tag{27}$$

$$\begin{aligned}\Delta OHC(j) = {} & N_{OM}\cdot\sum_{k=1}^{NWCT_{OM}(j)} NWC_{OM}(j,k)\cdot\left[OHC_{NEW}(j,OM,k) - OHC_{OLD}(j,OM,k)\right]\\ & + N_{IM}\cdot\sum_{k=1}^{NWCT_{IM}(j)} NWC_{IM}(j,k)\cdot\left[OHC_{NEW}(j,IM,k) - OHC_{OLD}(j,IM,k)\right]\\ & + N_{DM}\cdot\sum_{k=1}^{NWCT_{DM}(j)} NWC_{DM}(j,k)\cdot\left[OHC_{NEW}(j,DM,k) - OHC_{OLD}(j,DM,k)\right]\end{aligned} \tag{28}$$

The differential annual O&MN cost, denoted by $\Delta C_{O\&MN}(j)$, is then computed as follows:

$$\Delta C_{O\&MN}(j) = 12 \cdot \left[\Delta PC(j) + \Delta OC(j) + \Delta RMC(j) + \Delta OHC(j)\right] \tag{29}$$

where the PC(j) are outputs obtained in the personnel section. This output for each project combination is printed out in the Project Combination Sumary Output Table.

c. Turnaround Time Section

The model inputs for the turnaround time section of the computations are as follows, where j denotes the project combination number ($j=1, \ldots, N_{PC}$), m denotes the maintenance level (m=OM, IM, DM), and k denotes the work center type ($k=1, \ldots, NWCT_m(j)$):

$P_{OLD}(m)$ = proportion of all maintenance actions performed at maintenance level m under present system

$P_{NEW}(j,m)$ = proportion of all maintenance actions performed at maintenance level m under new system

T_{SIM} = average one-way shipping and receiving time for a repairable item from an organizational maintenance component to an intermediate maintenance component

TSDM = average one-way shipping and receiving time from an organizational maintenance component to a depot maintenance component

$P_{MA}(j,m,k)$ = proportion of maintenance actions performed at maintenance level m that go through this work center

$TAT_{OLD}(j,m,k)$ = average turnaround time for maintenance performed at this work center under present system

$TAT_{NEW}(j,m,k)$ = average turnaround time for maintenance performed at this work center under new system.

The first computations are directed to the determination of the total weighted average turnaround times for all the work centers affected by project combination j under the present and new systems, denoted respectively

by $TTAT_{OLD}(j)$ and $TTAT_{NEW}(j)$. These computations are performed in accordance with the following equations:

$$TTAT_{OLD}(j) = P_{OLD}(OM) \cdot \sum_{k=1}^{NWCT_{OM}(j)} P_{MA}(j,OM,k) \cdot TAT_{OLD}(j,OM,k)$$

$$+ P_{OLD}(IM) \cdot \sum_{k=1}^{NWCT_{IM}(j)} P_{MA}(j,IM,k) \cdot TAT_{OLD}(j,IM,k) + 2 \cdot T_{SIM}$$

$$+ P_{OLD}(DM) \cdot \sum_{k=1}^{NWCT_{DM}(j)} P_{MA}(j,DM,k) \cdot TAT_{OLD}(j,DM,k) + 2 \cdot T_{SDM} \tag{30}$$

$$TTAT_{NEW}(j) = P_{NEW}(j,OM) \cdot \sum_{k=1}^{NWCT_{OM}(j)} P_{MA}(j,OM,k) \cdot TAT_{NEW}(j,OM,k)$$

$$+ P_{NEW}(j,IM) \cdot \sum_{k=1}^{NWCT_{IM}(j)} P_{MA}(j,IM,k) \cdot TAT_{NEW}(j,IM,k) + 2 \cdot T_{SIM}$$

$$+ P_{NEW}(j,DM) \cdot \sum_{k=1}^{NWCT_{DM}(j)} P_{MA}(j,DM,k) \cdot TAT_{NEW}(j,DM,k) + 2 \cdot T_{SDM} \tag{31}$$

The differential total average turnaround time, denoted by $\Delta TAT(j)$, is then computed as follows:

$$\Delta TAT(j) = TTAT_{NEW}(j) - TTAT_{OLD}(j) \tag{32}$$

This output for each project combination is then printed out in the Project Combination Summary Output Table.

d. Model Output

The model output consists of two output tables: Summary of Research and Development Costs by R&D Project, and Project Combination Cost-Benefit Table.

The Summary of Research and Development Costs by R&D Project table presents the following information for each R&D project:

- R&D Project Number
- Project Name
- For each R&D phase and for the total project duration, the following information:
  - Months Duration
  - Start Month
  - End Month
  - Probability of Success
  - R&D Investment Cost
  - Probability of Termination (during the phase)
  - Expected Investment Loss Component (given termination during the phase)
- Expected Investment Loss Component (given successful project that is not used)
- Total Expected Investment Loss (given project is unsuccessful or not used)

An example of a computer printout of this table is presented in Figure IV-1 of the next section of this chapter.

The Project Combination Cost-Benefit Table presents the following information for each R&D Project Combination considered:

- Project Combination Name
- R&D Projects Included in Project Combination
- Total R&D Costs
- Total Investment Loss (for R&D projects not used)
- Total Manufacturing and Installation Costs
- Total Investment Costs
- Operations and Maintenance Start Month
- Differential Annual O&MN Costs
- Differential Turnaround Time
- Differential Number of Personnel Required
- Differential Average Utility Per Person (for work centers affected by project combination).

An example of a computer printout of this table is presented in Figure IV-2 of the next section of this chapter.

D. Sample Demonstration

1. Hypothetical R&D Program

The purpose of this section is to present a demonstration of the use of the Cost-Benefit Model in evaluating the cost-benefit aspects of a hypothetical AI/robotic application to Navy aircraft maintenance. This example assumes that a broad research and development program is initiated with the objective of automatizing much of the paint removal and painting activities at the three levels of aircraft maintenance. This R&D program consists of three R&D projects directed respectively to the development of an automatic masking robot, a robot acid sprayer, and a mobile robot painter. For this example, it is assumed that an automatic masking robot would not warrant implementation unless it could be used in conjunction with either a robot acid sprayer or a mobile robot painter. However, the robot acid sprayer or the mobile robot painter would be implemented regardless of the availability of the other robot systems. With these assumptions then there are six possible alternative systems that could be implemented at the end of the R&D program. These are as follows:

- Operator Assisted Paint Removal - based on the success of the Robot Acid Sprayer Project and the failure of the other two projects.
- Operator Assisted Robot Painter - based on the success of the Mobile Robot Painter Project and the failure of the other two projects.
- Automatic Paint Removal - based on the success of the Automatic Masking Robot and Robot Acid Sprayer Projects and the failure of the Mobile Robot Painter Project.
- Automatic Robot Painter - based on the success of the Automatic Masking Robot and Mobile Robot Painter Projects and the failure of the Robot Acid Sprayer Project.
- Operator Assisted Paint Removal and Robot Painter - based on the success of the Robot Acid Sprayer and Mobile Robot Painter Projects and the failure of the Automatic Masking Robot Project.

* <u>Automatic Paint Removal and Robot Painter</u> - based on the success of all three projects.

2. <u>Model Inputs</u>

The model inputs for this example are divided into four sets: R&D Project Inputs, Constant Inputs, Project Combination Inputs, and Work Center Personnel Requirements. The required inputs for the three R&D projects are presented in Table IV-1. Note that the Automatic Masking and Mobile Robot Painter Projects commence in the first month of the R&D program, while the Robot Acid Sprayer Project does not commence until the seventh month of the program.

The constant inputs are presented in Table IV-2. This set of inputs consist of data that are not project combination dependent. These include the numbers of organizational maintenance (OM), intermediate maintenance (IM), and depot maintenance (DM) components within the Navy-wide aircraft maintenance structure, and the number of work centers at each maintenance level that could be affected by implementation of any of the alternative AI/Robotic systems emerging from the R&D program. For this example, each maintenance level has only one affected work center type (OM-corrosion control work center, IM-airframes division, DM-paint shop) and only one such work center type at each maintenance component. In the model, it is assumed that, of the maintenance actions performed at a specific maintenance level, the proportion of these that go through a work center type will not be affected by the implementation of new systems, and so these are considered as constant inputs. Note, however, that the proportion of maintenance actions performed at the different maintenance levels (level-of-repair distribution) may be affected by implementation of new systems and thus these are considered as project combination-dependent inputs.

The inputs that are dependent on the specific project combination, with the exception of work center personnel requirements, are presented in Table IV-3. Note that some of the inputs are not required for the present system, which is denoted by Project Combination 0. These include the manufacturing and installation costs per system and the number of systems required at each work center type, in addition to the

Table IV-1

R&D PROJECT INPUTS*

R&D Project No.	Project Name	Start Month	R&D Phase	Months Duration	R&D Cost (K$)	Probability of Success
1	Automatic Masking	1	Basic Res.	6	250	0.90
			Expl. Dev.	12	350	0.85
			Adv. Dev.	12	750	0.80
			Eng. Dev.	18	1000	0.90
2	Robot Acid Sprayer	7	Basic Res.	6	200	0.95
			Expl. Dev.	8	300	0.95
			Adv. Dev.	10	500	0.90
			Eng. Dev.	12	500	0.95
3	Mobile Robot Painter	1	Basic Res.	6	250	0.95
			Expl. Dev.	12	300	0.90
			Adv. Dev.	18	800	0.85
			Eng. Dev.	12	500	0.95

* The inputs in this table are hypothetical in nature and are used for illustrative purposes only.

Table IV-2

CONSTANT INPUTS*

Input Description	Value
Number of OM Components	180
Number of IM Components	60
Number of DM Components	5
Number of Work Centers at Maintenance Level	
- OM Corrosion Control	1
- IM Airframes	1
- DM Paint Shop	1
Proportion of Maint. Level's Maint. Actions That Go Through Work Center:	
- OM Corrosion Control	0.1
- IM Airframes	0.3
- DM Paint Shop	0.3

* The inputs in this table are hypothetical in nature and are used for illustrative purposes only.

Table IV-3

PROJECT COMBINATION INPUTS*

Input Description	Project Combination						
	0	2	3	12	13	23	123
Manufacturing & Installation Time (Months)	--	12	12	15	15	18	18
Manufacturing Cost per System (K$)	--	30	40	60	70	70	100
Installation Cost per System (K$)	--	5	5	10	10	10	15
Number of Systems per Work Center:							
- OM Corrosion Control	--	1	1	1	1	1	1
- IM Airframes	--	1	1	1	1	1	1
- DM Paint Shop	--	2	2	2	2	2	2
Prop. of Maint. Actions Performed at OM Level	0.80	0.80	0.80	0.82	0.82	0.81	0.84
Prop. of Maint. Actions Performed at IM Level	0.15	0.15	0.15	0.14	0.14	0.15	0.13
Prop. of Maint. Actions Performed at DM Level	0.05	0.05	0.05	0.04	0.04	0.04	0.03
Monthly Operations Cost (K$):							
- OM Corrosion Control	5.0	7.0	7.0	8.0	8.0	8.0	9.0
- IM Airframes	10.0	12.0	12.0	13.0	13.0	13.0	14.0
- DM Paint Shop	40.0	44.0	44.0	46.0	46.0	46.0	48.0
Monthly Repair & Maintenance Cost (K$):							
- OM Corrosion Control	1.0	1.2	1.2	1.3	1.3	1.3	1.4
- IM Airframes	5.0	5.4	5.4	5.6	5.6	5.6	5.8
- DM Paint Shop	15.0	17.0	17.0	18.0	18.0	18.0	20.0
Monthly Overhead Cost (K$):							
- OM Corrosion Control	1.0	1.1	1.1	1.2	1.2	1.2	1.3
- IM Airframes	5.0	5.3	5.3	5.5	5.5	5.5	5.8
- DM Paint Shop	10.0	11.5	11.5	12.0	12.0	12.0	13.0
Average Turnaround Time (Hrs):							
- OM Corrosion Control	8	6	6	4	4	5	2
- IM Airframes	24	20	20	16	16	18	12
- DM Paint Shop	56	48	48	40	40	42	32

* The inputs in this table are hypothetical in nature and are used for illustrative purposes only.

time required for the manufacturing and installation of all required systems. The project combination inputs also include level-of-repair distribution and the monthly operations, repair and maintenance, and overhead costs associated with each work center type. The estimated average turnaround times for maintenance actions at each work center type are also included in this set of inputs.

The work center personnel requirements for each project combination, specified in standard Navy personnel nomenclature, are presented in Table IV-4. These inputs are listed in accordance with requirements for each applicable officer designator and pay grade, EM rating and pay grade, and civilian occupation code and pay scale level. Table IV-5 presents these inputs transformed to the utility data base structure which is used in the model computations.

3. Model Outputs

Figure IV-1 presents the R&D Project Summary Report. The Automatic Masking Project is the highest risk project with a probability of success of only 0.551 compared with 0.690 for the Mobile Robot Painter Project and 0.772 for the Robot Acid Sprayer Project. The Automatic Masking Project is also the highest cost project with an R&D investment cost, if successful, of $2.35 million compared with $1.85 million for the Mobile Robot Painter Project and $1.5 million for the Robot Acid Sprayer Project. The expected investment loss for the Automatic Masking Project, if unsuccessful, is $0.46 million. If successful but not used in a subsequent project combination representing an AI/Robotic application, the expected investment loss for this project is $1.29 million. Thus, the total expected investment loss for the Automatic Masking Project is $1.75 million if the project is not used in a subsequent project combination. For the Mobile Robot Painter Project, the expected investment losses are $0.30 million, if unsuccessful, and $1.28 million, if successful but not subsequently used, and the total expected investment loss is $1.58 million if not used in a subsequent project combination. For the Robot Acid Sprayer Project, the respective expected investment losses are $0.18 million and $1.16 million, with a total expected investment loss, if not used in a subsequent project combination, of $1.34

Table IV-4

WORK CENTER PERSONNEL REQUIREMENTS*

(Normal Nomenclature)

Work Center Type	Billet Title	Des/ Rate/ Code	Pay Grade	Number of Personnel — Project Combination 0	2	3	12	13	23	123
OM Corrosion Control	Supervisor	1321	O-3	1	1	1	1	1	1	1
	Av. Structures Mech.	AMS	E-6	1	1	1	1	1	1	1
	Av. Structures Mech.	AMS	E-5	2	2	2	1	1	1	1
	Av. Structures Mech.	AMS	E-4	3	3	3	3	3	3	2
	Av. Structures Mech.	AMS	E-3	4	3	3	2	2	2	2
IM Airframes	Supervisor	AMH	E-7	1	1	1	1	1	1	1
	Av. Hydraulics Mech.	AMH	E-6	1	1	1	1	1	1	1
	Av. Hydraulics Mech.	AMH	E-5	3	3	3	3	3	3	3
	Av. Hydraulics Mech.	AMH	E-3	2	2	2	2	2	2	2
	Av. Structures Mech.	AMS	E-8	1	1	1	1	1	0	0
	Av. Structures Mech.	AMS	E-7	0	0	0	0	0	1	1
	Av. Structures Mech.	AMS	E-6	1	1	1	1	1	1	1
	Av. Structures Mech.	AMS	E-5	4	3	3	3	3	2	1
	Av. Structures Mech.	AMS	E-4	4	4	4	3	3	2	2
	Av. Structures Mech.	AMS	E-3	1	1	1	1	1	1	1
	Mach. Repairman	MR	E-6	1	1	1	1	1	1	1
	Mach. Repairman	MR	E-4	0	0	0	0	0	1	1
DM Paint Shop	Supervisor	37	WS-9	1	1	1	1	1	1	1
	Electroplater	37	WG-9	6	5	5	5	5	4	4
	Electroplater	37	WG-7	7	6	6	5	5	5	4
	Electroplater	37	WG-5	5	5	5	4	4	4	3
	Buffer/Polisher	34	WG-8	2	2	2	2	2	2	2
	Painter	41	WS-9	3	3	3	3	3	3	2
	Painter	41	WG-9	26	24	24	20	21	16	14
	Painter	41	WG-7	24	22	22	19	18	14	12
	Equip. Cleaner	70	WG-6	1	1	1	1	1	1	1
	Equip. Maint.	26	WG-7	0	1	1	1	1	1	1

* The inputs in this table are hypothetical in nature and are used for illustrative purposes only.

Table IV-5

WORK CENTER PERSONNEL REQUIREMENTS *
(Utility Nomenclature)

Work Center Type	Utility Pay Grade	Utility Skill Group	Number of Personnel						
			Project Combination						
			0	2	3	12	13	23	123
OM Corrosion Control	12	2	1	1	1	1	1	1	1
	6	3	1	1	1	1	1	1	1
	5	3	2	2	2	1	1	1	1
	4	3	3	3	3	3	3	3	2
	3	3	4	3	3	2	2	2	2
IM Airframes	8	3	1	1	1	1	1	0	0
	7	3	1	1	1	1	1	2	2
	6	3	2	2	2	2	2	2	2
	6	5	1	1	1	1	1	1	1
	5	4	0	0	0	0	0	1	1
	5	3	7	6	6	6	6	5	4
	4	3	4	4	4	3	3	2	2
	3	3	3	3	3	3	3	3	3
DM Paint Shop	10	7	3	3	3	3	3	3	2
	10	6	1	1	1	1	1	1	1
	5	7	26	24	24	20	21	16	14
	5	6	6	5	5	5	5	4	4
	4	7	24	22	22	19	18	14	12
	4	6	9	8	8	7	7	7	6
	4	4	0	1	1	1	1	1	1
	3	7	1	1	1	1	1	1	1
	3	6	5	5	5	4	4	4	3

* The inputs in this table are hypothetical in nature and are used for illustrative purposes only.

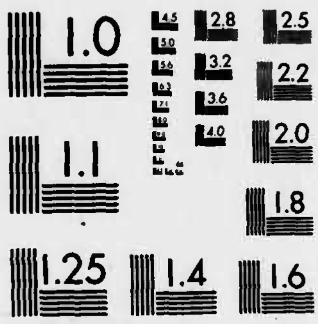
SUMMARY OF RESEARCH AND DEVELOPMENT COSTS BY R&D PROJECT*

R&D PROJECT NUMBER	R&D PROJECT NAME	R&D PHASE	MONTHS DURATION	PERIOD START MONTH	PERIOD END MONTH	PROBABILITY OF SUCCESS	R&D INVESTMENT COST (K$)	PROBABILITY OF TERMINATION	EXPECTED INVESTMENT LOSS (K$)
1	AUTOMATIC MASKING	BASIC RES.	6	1	6	0.900	250.00	0.100	25.00
		EXPL. DEV.	12	7	18	0.850	350.00	0.135	81.00
		ADV. DEV.	12	19	30	0.800	750.00	0.153	206.55
		ENG. DEV.	18	31	48	0.900	1000.00	0.061	143.82
		TOTAL PROJ	48	1	48	0.551	2350.00	0.449	1294.38
								TOTAL	1750.75
2	ROBOT ACID SPRAYER	BASIC RES.	6	7	12	0.950	200.00	0.050	10.00
		EXPL. DEV.	8	13	20	0.950	300.00	0.048	23.75
		ADV. DEV.	10	21	30	0.900	500.00	0.090	90.25
		ENG. DEV.	12	31	42	0.950	500.00	0.041	60.92
		TOTAL PROJ	36	7	42	0.772	1500.00	0.228	1157.46
								TOTAL	1342.38
3	MOBILE ROBOT PAINTER	BASIC RES.	6	1	6	0.950	250.00	0.050	12.50
		EXPL. DEV.	12	7	18	0.900	300.00	0.095	52.25
		ADV. DEV.	18	19	36	0.850	800.00	0.128	173.14
		ENG. DEV.	12	37	48	0.950	500.00	0.036	67.22
		TOTAL PROJ	48	1	48	0.690	1850.00	0.310	1277.26
								TOTAL	1582.38

* The results presented in this table are hypothetical in nature and are used for illustrative purposes only.

Figure IV-1 LISTING--R&D PROJECT SUMMARY REPORT

AD-A143 219 ARTIFICIAL INTELLIGENCE/ROBOTICS APPLICATIONS TO NAVY 2/3
AIRCRAFT MAINTENANCE(U) SRI INTERNATIONAL MENLO PARK CA
D R BROWN ET AL. JUN 84 SRI-4905 DTNSRDC/CMLD-CR-53-84
UNCLASSIFIED N00600-82-D-8362 F/G 5/1 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

million. If successful, both the Automatic Masking Project and the Mobile Robot Painter Project will require 4 years of R&D, while the Robot Acid Sprayer Project will require only 3 years of R&D, although the manufacturing and installation phase could not commence until the middle of the fourth year since the start of R&D on this project was delayed until the middle of the first year of the R&D program.

The major outputs of the computer model are presented in the Project Combination Cost-Benefit Table as displayed in Figure IV-2. The six project combinations that represent possible AI/Robotic applications that could result from proposed R&D programs are listed in the first column of the table. The project combinations were specified as input in increasing order of complexity, beginning with individually useful R&D projects, then doubly useful R&D project combinations, and finally the ultimate combination of all three R&D projects. The next three columns represent the components that contribute to the Total Investment Costs presented in Column 5. The Total R&D Costs (Column 2) and Expected Investment Losses (Column 3) are derived from the R&D Project Summary Report (Fig. IV-1), while the Total M&I Costs are computed from the manufacturing and installation cost inputs for the applicable systems to be implemented. The O&M Start Month (Column 6) adds the manufacturing and installation time required for full system implementation to the date of completion of R&D, which is the latest date of completion of the applicable R&D projects. The differential outputs of Annual O&MN Costs, Turnaround Time, Number of Personnel Required, and Average Utility per Person (Columns 7-10) represent the differences in the expected values of the factors between the new systems and the present system.

The first two systems, the Operator Assisted Paint Removal System and the Operator Assisted Robot Painter System, are based on individually useful R&D projects. The former has expected Total Investment Costs of $13.6 million and an implementation date at the beginning of the 55th month after the initiation of the R&D program, while the latter system has Total Investment Costs of $16.2 million with an implementation date of the 61st month. Since the only project combination input that varied between these two systems was the manufacturing cost per system (included in the Total Investment Costs), the remaining

PROJECT COMBINATION COST-BENEFIT TABLE*

PROJECT COMBINATION	TOTAL R&D COSTS (K$)	EXPECTED INVESTMENT LOSS (K$)	TOTAL M&I COSTS (K$)	TOTAL INVESTMENT COSTS (K$)	O&M START MONTH	DIFFERENTIAL ANNUAL O&MN COSTS (K$)	DIFFERENTIAL TURNAROUND TIME (HOURS)	DIFFERENTIAL NUMBER OF PERSONNEL REQUIRED	DIFFERENTIAL AVERAGE UTILITY PER PERSON
OPER ASST PNT RMVL R&D PROJS-2	1500.00	3333.13	8750.00	13583.13	55	3312.83	-0.46	-265.0	0.00628
OPER ASST RBT PNTR R&D PROJS-3	1850.00	3093.13	11250.00	16193.13	61	3312.83	-0.46	-265.0	0.00628
AUTO PNT RMVL R&D PROJS-12	3850.00	1582.38	17500.00	22932.38	61	-448.14	-1.27	-730.0	0.01328
AUTO RBT PNTR R&D PROJS-13	4200.00	1342.38	20000.00	25542.38	64	-437.40	-1.27	-730.0	0.01329
OA PNT RMVL/RBT PNTR R&D PROJS-23	3350.00	1750.75	20000.00	25100.75	67	-2416.56	-0.98	-840.0	0.01509
AUTO PNT RMVL&PNTR R&D PROJS-123	5700.00	0.00	28750.00	34450.00	67	-3107.77	-2.02	-1115.0	0.01809

* The results presented in this table are hypothetical in nature and are used for illustrative purposes only.

Figure IV-2 OUTPUT LISTING--COMBINATION COST-BENEFIT TABLE

values of the cost-benefit factors are the same. The Number of Personnel Required is 265 less than the present system, although the Average Utility per Person increased by .0063. This latter increase infers that the personnel decreases obtained are weighted more toward utility billets below the present system's average than above it. The Annual O&MN Costs increase by $3.3 million over the present system which infers that the savings in annual personnel costs do not negate the increases in operations, repair and maintenance, and overhead costs associated with the new systems. However, the Overall Maintenance Turnaround Time does decrease by almost one-half hour for the new systems as opposed to the present system.

The next three systems, the Automatic Paint Removal System, the Automatic Robot Painter System, and the Operator Assisted Paint Removal and Robot Painter System, are based on doubly useful R&D projects. The Total Investment Costs for these systems range from $22.9 million to $25.5 million, with implementation start date ranging from the 61st month after R&D program start to the 67th month. The Automatic Paint Removal System and the Automatic Robot Painter System each provide a decrease of 730 in the Number of Personnel Required from the present system, at an increase of .0133 in Average Utility per Person. This decrease in personnel requirements is sufficient to reduce the Annual O&MN Costs by about $0.44 million. In addition, these systems, both of which incorporate an automatic masking system, reduce the Overall Maintenance Turnaround Time by about 1.3 hours from that attributable to the present system. The Operator Assisted Paint Removal and Robot Painter System provides a decrease of 840 in the Number of Personnel Required from the present system, although the Average Utility per Person increases by about 0.0151 utiles. This system reduces the Overall Maintenance Turnaround Time by about one hour and, more significantly, provides a reduction of about $2.4 million in Annual O&MN Costs. This increase in savings from the other two systems in this category (doubly useful R&D projects) is attributable to an increased reduction of 110 personnel and illustrates the impact of personnel costs on the Annual O&MN Costs.

The final system, the Automatic Paint Removal and Robot Painter System, represents the total fruition of all three R&D projects in the R&D Program. The Total Investment Costs for this system would be about $34.5 million, with an implementation start date during the 67th month following the commencement of the R&D Program. This system would provide a reduction of 1115 in the Number of Personnel Required from the present system, although increasing the Average Utility per Person by about 0.0181 utiles. The decrease in personnel requirements provides a decrease of about $3.1 million in Annual O&MN Costs, even after considering the increase in the annual costs for operations, repair and maintenance, and overhead. In addition, the Overall Maintenance Turnaround Time is reduced by two hours from that attainable with the present system.

The results discussed above are based on hypothetical input values and should not be construed as representative of results to be obtained from real input data. They have been presented merely to provide a demonstration of the use of the cost-benefit model in producing useful cost-benefit data for assistance in making decisions relative to planning R&D programs aimed at the enhancement of aircraft maintenance efficiency as a result of implementing AI/Robotic's systems into the Navy aircraft maintenance system.

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Appendix A

SURVEY OF AI/ROBOTICS

CONTENTS

Appendix A

SURVEY OF AI/ROBOTICS

1. Introduction

The objective of the research described in this appendix was to conduct a survey of existing and projected artificial intelligence (AI) and robotics techniques that might be useful, in the foreseeable future, to the enhancement of Navy aircraft maintenance efficiency.

The results of this survey are presented in Chapter 2. This chapter is primarily excerpted from SRI Report ETL-0296, "R&D Plan for Army Applications of AI/Robotics," prepared for the U.S. Army Engineer Topographic Laboratories, May 1982, under Contract Number DAAK70-81-C-0250. It has been updated to reflect recent developments in AI/Robotics technology.

A bibliography organized by subject area appears at the end of this appendix.

2. Artificial Intelligence and Robotics

a. Introduction

To be able to perform human tasks, an intelligent robot should be able to think, sense, and effect (move and manipulate). The thinking or "brain function," executed by a computer, is the domain of artificial intelligence. Sensing and effecting are "body functions"; they are based on physics, mechanical engineering, electrical engineering, and computer science. These functions are the domain of robotics. Planning and execution of tasks entail both brain and body, and so are affected by both artificial intelligence and robotics. We will not attempt to distinguish between artificial intelligence and robotics but will present a model that encompasses both.

There are two basic goals of the research in these areas: to make computers smarter and to improve our understanding of human intelligence. The latter is also sometimes called "cognitive science" or "cognitive psychology." These two goals do not necessarily conflict, and, in fact, many researchers work toward both. For the purposes of this appendix, we will concentrate on research with the goal of making computers smarter.

Artificial intelligence and robotics are really in their infancy, but their promise is great. Some practical applications of this research are appearing, although in most cases they are limited and aimed at solving specific problems. Current research is directed towards both extending the capabilities of current applications and finding more general solutions to the problems they address.

In this chapter we outline the current state of artificial intelligence and robotics and the basic research issues being addressed. We focus on some of the problems that must be solved before certain aspects of intelligence will be available in computers. A bibliography organized by subject area appears at the end of this appendix. Individual research is generally not cited in this chapter.

Before discussing what artificial intelligence and robotics are, we will briefly mention who is doing research in these areas and where.

b. Background

The number of researchers in artificial intelligence and robotics is rapidly expanding with the increasing number of applications and potential applications of the technology. This growth is not only in the United States, but worldwide, particularly in Europe and Japan.

Basic research is going on primarily at universities and some research institutes. Originally, the primary research sites were MIT, CMU, Stanford, SRI, and the University of Edinburgh. Now, most major universities include artificial intelligence and/or robotics in the computer science curriculum.

An increasing number of other organizations either have established or are establishing research laboratories for artificial intelligence and robotics. Some of them are conducting basic research, others are primarily interested in applications. These organizations include: Digital Equipment Corporation, Xerox, Hewlett-Packard, TRW, Texas Instruments, Schlumberger-Fairchild, Hughes, NASA, Jet Propulsion Laboratory, Charles S. Draper Laboratories, Rand, ISI, Lockheed, Allen-Bradley, duPont, Kodak, Honeywell, Kulick & Soffa Industries, Lord Corporation, Proctor and Gamble, RCA, E.G.&G. Reticon, United Technologies, Universal Instruments, McDonnell-Douglas, Boeing, Northrup, Martin-Marietta, Rand, Perceptronics, PAR, Unilever, and Philips. Japanese companies include Hitachi, Kawasaki, Fujitsu, NTT, NEC, Toshiba, and Hamamatsu.

Also emerging are companies that are developing artificial intelligence and/or robotics products. U.S. robot developers include: Unimation, Cincinnati Milacron, IBM, General Electric, Westinghouse, Copperweld, Industrial Robots International, General Motors, U.S. Robots, Bridgeport Tool Co., Teleoperator Systems, Thermwood, MIC, Automatix. Some European robot manufacturers include Renault, Volkswagen, Olivetti, D.E.A. Japanese robot manufacturers include Kawasaki, Hitachi, Mitsubishi, Yaskawa, Fujitsu, and many smaller companies.

Some U.S. companies specializing in artificial intelligence are Teknowledge, Intelligenetics, Cognitive Systems, Smart Systems, Artificial Intelligence Corp, Symantec, and Kestrel Institute.

As can be seen from these lists, only the largest companies--foreign or domestic--can afford to develop both robots and artificial intelligence simultaneously. Even then they are usually separate and independent efforts.

c. A Unified Model for Artificial Intelligence and Robotics

Figure A-1 can be viewed as a simplified model of an intelligent system. We will use it as a model for artificial intelligence and robotics. The major components are:

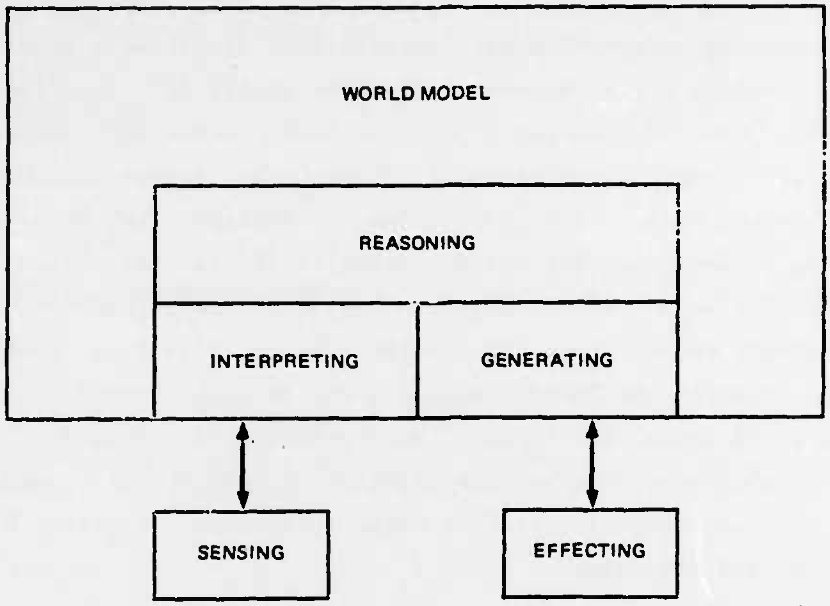

Figure A-1 A UNIFIED MODEL OF ARTIFICIAL INTELLIGENCE AND ROBOTICS

* Sensing
* Effecting
* Interpreting
* Generating
* Reasoning.

The last three of these draw heavily on knowledge about the world and how it works. The parts of the model should not be viewed as isolated pieces, but rather clusters of related functions. We will describe the model briefly here and discuss the components in more detail in the following sections.

This model of artificial intelligence and robotics emphasizes intelligent functions that are performed. Underlying them are more fundamental research issues that are concerned with:

* Representing the knowledge needed to act intelligently
* Acquiring knowledge and explaining it effectively

* Reasoning: drawing conclusions, making inferences, making decisions
* Acting with knowledge that is incomplete, uncertain, and perhaps conflicting
* Evaluating and choosing among alternatives.

Advances in artificial intelligence and robotics require advances in these fundamental areas and the capabilities of intelligent functions (e.g., vision).

i. Sensing and Effecting

Sensing and effecting, the parts of the model at the bottom of Figure A-1, are primarily directed towards interacting with the environment. Sensing includes activities such as seeing, hearing, touching, smelling, and measuring distance. Effecting includes moving, object handling, and speaking. A characteristic of these actions is that they depend on heavy interaction with the environment, but very little (if any) ability to reason about it. They basically collect information, or produce information or action.

Sensing covers the basic input to a system with perhaps some limited processing that is performed independent of the use of the information. Input can be in many forms: pictures, radar, data, speech, typed input, and graphical input (charts, maps). This part includes simple processing, but nothing that requires any knowledge about the content of the input or the reasons for gathering it. For example, we might include formant tracking on a speech wave as part of sensing, but not word identification. Similarly, some simple edge-detection methods would fall in this area if they only work on local changes in the digitized image and do not require information about the objects or background.

Companion to sensing (input) is effecting (output), that is, producing some signal/information or moving about. Again, some of the topics here are concerns of artificial intelligence and robotics, others fall under other disciplines. Under effecting we include systems that

perform with some local control, but do not ´reason´ about what they are doing. Effectors can be manipulators (hands, arms), legs, wheeled vehicles, and various means of communication (e.g., sounds, graphics, and pictures).

Some aspects of these areas are concerns of artificial intelligence and robotics, others are concerns of disciplines such as physics, mechanical engineering, electrical engineering, and computer science. We will focus on topics that are concerns of robotics or artificial intelligence.

ii. Knowledge About the World

In any sophisticated interaction with its environment, an intelligent system must have some knowledge about that environment including:

* What objects are, or could be, around, e.g., trees, rocks, lakes, rivers, people, vehicles
* Actual and possible properties of the objects, e.g., size, shape, color, texture
* Their possible relationships with other objects, e.g., above, below, behind
* Changes that can occur and how they affect the situation, e.g., cutting down a tree destroys it; repairing an aircraft makes it usable.

As we have mentioned, questions about how to represent, acquire, and explain this knowledge in a computer system are part of the fundamental research in artificial intelligence and robotics.

The parts of the model we call interpreting, generating, and reasoning all require some knowledge about the world. Furthermore, they all use that knowledge for some purpose, such as,

* Understanding the environment, e.g., recognizing and locating objects, and detecting changes in the environment.
* Planning and carrying out actions to affect the environment, e.g., assembling objects, moving about.

iii. Interpreting

Interpreting information is the means by which an intelligent system understands its environment. The information can be acquired through perceptual processes or other means (e.g., a data base). We will focus on interpreting images, both visual and those provided by other sensors (e.g., radar, sonar) and interpreting language (written or spoken).

Images are interpreted for many reasons including: detecting, recognizing, and locating objects, detecting change (e.g., movement of objects), and describing unknown objects. Research is directed towards better methods for acquiring images, extracting information from the images and using knowledge about the objects.

There are two main reasons for developing computer systems that can interpret language: to improve a person's interaction with the machine and to facilitate the processing of textual information by a computer. For example, a person may interact with a computer in order to give it commands, query various data bases, or conduct a dialog with some advice-giving system or teaching system.

Textual information may be processed in order to translate it, summarize it, or perhaps integrate it with other information. In each case the information must not just be 'read' but in some sense 'understood.'

iv. Generating

The part of the model labeled "generating" refers to the processes by which an intelligent system decides to influence its environment. This effect may be through direct or indirect action. Direct actions include manipulating objects, using hands and arms to assemble objects, and navigating a vehicle, avoiding obstacles and possibly replanning paths.

Examples of indirect actions include generating language and/or pictures in order to convey information to a person (or another system).

The concerns of language and graphics generation are basically deciding what to say, and how best to say it.

v. Reasoning

The ability to cope with unforeseen, incomplete, uncertain, and perhaps conflicting information and to act and react to it is a prerequisite of any intelligent behavior. This ability is what we have labeled as reasoning in the final part of the model. Basic research is directed toward discovering and developing the underlying mechanisms necessary for reasoning.

Intelligent systems reason for many purposes, these include:

* Helping interpret sensory information
* Helping decide what effectors and sensors to use and how to use them
* Planning actions and monitoring their execution
* Solving problems
* Gathering new information
* Diagnosing a situation
* Recognizing a situation.

In the sections on interpretation and generation, we will discuss reasoning as it is used for interpreting and generating information. In Section h we will discuss other uses of reasoning and the research problems associated with developing computer systems for them.

d. Sensing

A wide variety of devices can be used by an AI/robotic system to obtain information. They include not only transducers for physical quantities, such as microphones for sounds, but data processing input devices such as keyboards for textual information and specialized military sensors such as NBC contamination detectors. In this report we treat all these devices as different kinds of sensors.

For military applications there is an important distinction between sensors that emit energy or matter (active sensors) and those that do not (passive sensors). Passive sensors are preferable when stealth is required.

The act of sensing is, in general, performed in two steps:

(1) Transducing--converting the energy, physical condition, etc. that is to be sensed into a signal, usually electrical.

(2) Preprocessing--improving the signal by noise reduction, averaging, filtering, data compaction, and the like.

While transducing methods are usually highly specialized to one type of external condition or influence, preprocessing methods are often generally applicable to signals from many different kinds of transducer.

i. Important Sensors for Robotics

Omitting sensors for which development is already strongly driven by military or data-processing needs, such as radar or keyboards, the most important types of sensors for robotics are solid-state television cameras, range sensors, tactile sensors, and proprioceptors. The following sections each discuss the state-of-the-art of one of these sensors in terms of capabilities and limitations of commercially-available equipment. They then describe advanced prototypes now in laboratories, and extrapolate future developments. In Section f we will discuss "interpretation"--the problems associated with understanding the environment from sensor information.

ii. Visual Sensors

Visual sensors, using television cameras, are needed for seeing what is around the robot. For robotic applications, solid-state cameras are preferred over those with vacuum-tube imagers such as vidicons because of their ruggedness, low image distortion, low power requirements, and small size.

Today's solid-state television cameras can operate on either visible or infrared light. The highest image resolution available (800 by 800 pixels) is now about twice that of broadcast television, and the fastest cameras can take 2,000 pictures per second (as compared to 30 for broadcasting). Some imaging chips can even do simple image processing operations themselves, such as edge enhancement.

The main limitation of present-day solid-state cameras is that (except for one made by Hitachi) they do not take color pictures. Another problem is that they produce information much faster than a large conventional computer can process it, and most of it is highly redundant and uninformative.

Laboratory prototype camera chips now do some global image processing, such as Fourier transforms. Nondestructive-readout cameras can store an image for hours and the image can also be modified by a computer while it is stored.

2000 x 2000-pixel resolutions should be available within about ten years. But, to reduce the amount of image data to be processed, some cameras may have only a small high-resolution region near the center of their field of view ("foveal cameras").

iii. Tactile Sensors

Tactile sensors either detect when the hand touches something, or they measure some combination of force and torque components that the hand is exerting on an object. They usually use a number of strain gauges as transducers. However, a wide variety of simple, inexpensive devices such as microswitches can be used if it is only necessary to sense touch.

Force/torque sensors today use about eight strain gauges to measure the direction and magnitude of a force up to about 50 pounds with an accuracy of about one ounce. They can simultaneously measure the torque in any direction with comparable accuracy.

Today's off-the-shelf force/torque sensors are too insensitive to handle objects lighter than a few ounces. They are also too large for use on miniaturized robots, are rather delicate, and are expensive ($3,500-$8,000). Commercially-available touch sensors are not well-designed for use on robots.

Arrays of pressure sensors have been fabricated with about two sensors per mm resolution in two dimensions.

Materials such as carbon fibers, fiber optics, and doped plastic films may make possible large, flexible sheets of artificial "skin" with embedded touch (or other) sensors.

iv. Range Sensors

Range sensors are an important means of determining where objects are with respect to the robot.

In-air acoustic range sensors are accurate to about one millimeter over several meters. Laser range finders are accurate to about one meter over a kilometer; with a retroreflector on the target, however, they can easily measure to about a millimeter accuracy.

The main drawback to current range finders is that they must be scanned slowly over a scene in order to determine the 3-dimensional shape of the terrain and objects. The transverse resolution (beamwidth) of acoustic rangers and the range resolution of laser rangers is too coarse to be useful in many manipulation tasks.

A scanning laser ranger has been developed that simultaneously measures the reflectance of an object as well as its distance. This produces precisely-registered range and intensity images.

Electro-optical devices that operate in picoseconds are now being developed. These promise to improve the resolution of laser rangers to the millimeter range without the need for a retroreflector on the target object. Three emerging technologies promise tremendous increases in speed of processing range data and images over present-day electronic silicon devices. These are gallium arsenide, all-optical transistors, and Josephson junctions.

v. Proprioceptors

Proprioception in robotics means sensing the posture of a mechanical manipulator, leg, or other jointed mechanism. This is used mainly in two ways: in controlling the mechanism whose posture is sensed, and in sensing the posture of a teleoperator master arm in order to command the motion of a slave arm.

Proprioception involves measuring the angle of each rotary joint and the extension of each telescoping joint in a mechanism. The joint position sensors are usually either potentiometers, resolvers, or encoders.

Today, joint position sensors are accurate enough to enable a six-joint manipulator to place its hand anywhere within a three-meter-radius working volume with one-millimeter accuracy.

Highly-accurate sensors for joint angles or extensions are delicate, expensive, and difficult to manufacture. They are also too large for use in miniaturized robots.

In future, it may prove easier to measure the position of the hand directly than to infer it from accurate measurements of each joint position.

e. Output/Effectors

As we did for sensor technology in the preceding section, we will first list the important robotic effectors, then describe the state of the art and extrapolate future progress for each. In Section g we will discuss "generation"--the problems associated with using these effectors intelligently.

i. Important Effectors for Robotics

Omitting effectors for which development is already strongly driven by military or data-processing needs, such as weapons or displays, the most important types for robotics are devices that produce certain types of motion. It is convenient to group them loosely into "legs" that move

the entire robot over the terrain, "arms" with a range of motion on the order of the size of the robot itself, and "hands" that are positioned by the arms and have a much smaller range of motion. All of these are strongly dependent on the important supporting technology of mechanical actuators--electric, hydraulic, and pneumatic--which we do not have space to treat in this report.

The following sections each discuss one of these effectors in terms of capabilities and limitations of commercially-available equipment. They then describe advanced prototypes now in laboratories, and extrapolate future developments. We will also discuss the control of locomotion systems in Section and the control of hands and arms in Section ii.

ii. Hands

Commercially-available hands today are usually clamps with two or three jaws. The jaws are most often operated pneumatically, so that they are always held either open or closed with full force. Most general-purpose grippers offered today can hold parts weighing up to ten pounds and up to a few inches across.

The main problem with commercial grippers is that they are too clumsy for anything but simple handling tasks. Most of them are only suitable for use on the smaller manipulators; hands for large manipulators usually have to be engineered for each different task.

Two new robot hands have recently appeared on the market. One is a laboratory-grade three-fingered hand with three joints per finger. It is intended to be dexterous enough for complex manipulation tasks such as assembly. It has ten motors, tension-cable drives, and joint-torque sensing. The other new hand has two fingers, tactile sensing, and a built-in camera. It is intended for the industrial market.

Visual and tactile sensors will be incorporated into robot hands. Hands will have built-in computers to co-ordinate the motions of their fingers in order to grasp objects and move them precisely.

iii. Arms

More than a hundred different companies around the world now make manipulator arms. They range in size from tiny arms for handling near-microscopic hybrid circuit components up to machines that can lift objects weighing several hundred pounds four or five meters into the air. Typical positioning accuracies are about one millimeter and speeds about one or two meters/second.

Older arms resemble a tank turret with a hand on the end of a telescoping gun. Modern ones usually have five or six rotary joints in series, and move in somewhat the same way as a human arm does. Recently, several "Cartesian" manipulators have appeared on the market that have three orthogonal sliding joints for rigidity and ease of control. An arm is usually designed for a particular type of activity such as spraying, simple handling, or precise assembly.

Today's arms are expensive, complex, heavy, inefficient, and weak for their size. They can only lift about 5 percent of their own weight at best (compare this performance to a human arm!). Arms also tend to be rather specialized. Those that are good for a task like spraying are not suitable for precise assembly, for example.

A prototype arm has been developed whose motors are directly coupled to the joints without gears to give force control as well as improved speed and accuracy. Another arm is very compliant instead of being rigid like most industrial arms. A Japanese company has announced a multisegment "tentacle" arm for inspection of nuclear reactors. A multimillion-dollar project has also begun in Japan to develop "artificial muscles" based on biotechnology to replace electric and hydraulic motors in robots as well as other products. There is great interest in the U.S. in finding replacements for conventional electric motors or hydraulic actuators. Some technologies being evaluated include certain gels that reversibly increase in volume by 100% under electrical stimulation, piezoelectric materials such as PVF2 plastic and gadolinium molybdate crystals.

Parallel-joint manipulators and micromanipulators are about to move from the laboratory to the marketplace in England and New Zealand. These will make possible rapid, delicate motions for assembling electronic equipment and precision instruments.

The physical complexity of arms will decrease as ways are found to integrate joints, actuators, and sensors into the structure of the arm itself. New materials such as carbon fiber composites will lead to lighter, stiffer arms that can move more quickly and accurately with less effort. "Elephant trunks" or "tentacles" will be built with more joints and better performance. Micromanipulators will be developed for handling very small objects. Teleoperator master controls will be developed that are smaller, cheaper, and more convenient to use than the "full-scale model" ones in use today.

iv. Legs

By "legs" we mean not only mechanical legs, but all the conventional locomotion methods now used by Navy platforms, such as wheels, tracks, wings, and boats. Although each of these will be a very important means of locomotion for military robots, the technologies for conventional locomotion are strongly driven by other needs. Therefore, we will not discuss them here, but concentrate on mechanical legs. Furthermore, since there are no commercial versions of mechanical legs on the market at present, we omit discussion of their capabilities and limitations and begin with laboratory prototypes.

Mechanical legs may prove very useful in certain terrain conditions that defeat other locomotion methods. Thus they are more likely to play a role in Marine Corps operations than in most naval sea and air operations. The technology is still in its infancy, however.

Several robots have been built in laboratories around the world that walk on one leg, two legs, four legs, and six legs. The simpler models merely drive the legs through a fixed motion pattern without regard to terrain or body attitude. The more advanced models control the torques exerted by each leg joint to respond to instantaneous conditions.

Practical mechanical legs will be developed. They will probably require significant advances in actuator technology, since they will at least have to outperform present-day manipulators in terms of strength to weight ratio.

f. Interpreting

In this section we will discuss artificial intelligence and robotics research associated with interpreting sensory information, covering the areas of

* Computational Vision
* Natural Language Understanding (spoken or written).

i. Computational Vision

The general goal of computational vision is developing mechanisms for interpreting visual images. Interpreting images can be described as the process of going from a video (or other) signal to a symbolic description of it. (A symbolic description might be "That is a forest" or "A man is standing by the rock.") The same image may, in fact, have many descriptions depending on the reasons for processing it. One goal may be to count all the objects in an area, another may be to describe them, another may be to determine their exact location (without identifying them), and another to find irregularities in the terrain that can pose navigation problems.

Among the reasons for interpreting images are:

* Identifying objects
* Locating objects
* Detecting changes
* Navigating
* Describing a scene
* Making maps and charts.

(1). Current Status

We will cover the current state of computational vision in three areas: commercially available devices, systems and techniques that are undergoing laboratory development or testing, and basic research problems.

The commercial systems that are available are principally for industrial use. Suppliers include Machine Intelligence Corporation, Automatix, General Electric, and Bausch and Lomb. These systems can identify and locate objects in a controlled environment with the following restrictions:

* The number of possible objects that can be identified is limited.
* The number of objects in the scene is limited.
* The objects do not overlap.
* The object is always viewed vertically.
* The image features of an object are extracted from its binary image (silhouette).
* The objects are illuminated so as to obtain high dark-to-light contrast.

Typically, a system is trained to distinguish among objects by showing it sample objects. It will find outlines of each object and, using various techniques, develop a classification so it can distinguish the different types.

More sophisticated processing techniques for identifying and locating objects are being developed and tested in laboratories. For example, instead of requiring that the entire outline of an object be visible, some knowledge about the shape of the objects is used to "fill in" any edges that may be obscured by objects, shadows, or perhaps poor lighting. Other techniques include:

* Use of gray-scale information
* Use of 3-dimensional information
* Use of color, texture, and other attributes.

In general, this research will lead to more flexibility in the images that can be processed, including the following capabilities:

* Identifying objects that overlap
* Accommodating for a change in perspective
* Fewer requirements on lighting conditions.

In addition to industrial devices, systems for interpreting images for purposes other than industrial automation are in the laboratory stage. Two such areas are the automatic or semi-automatic interpretation of aerial imagery, e.g., for cartography and the interpretation of chest x-rays.

The development of these systems can be viewed as a movement in the diagram in Figure A-1 from sensing (simple processing of sensory input) to interpreting as more knowledge about the objects in the images and procedures for using it become incorporated.

Basic research in computational vision is devoted to understanding how further knowledge and reasoning can be used to interpret images, particularly so-called 'natural scenes', such as those found outdoors, where there are no restrictions on the environment, the objects, or the lighting.

Two major thrusts can be seen in current research. They are generally referred to as high-level vision and low-level vision.

High-level vision is concerned with combining knowledge about objects (shape, size, relationships), expectations about the image (what might be in it), and the purpose of the processing (identifying objects, detecting changes) to aid in interpreting the image. This high-level information interacts with, and helps guide, processing. For example, it can suggest where to look for an object, and what features to look for.

Low-level vision is concerned with extracting local data without the use of more general types of knowledge. This includes the problems associated with determining the physical characteristics of objects and scenes and how they influence perception. Physical properties include: surface reflectance, surface orientation, and incident illumination.

(2). Research Issues

Although vision systems are becoming available, there are many remaining research problems. They include:

* Representing knowledge about objects, particularly shape and spatial relationships
* Developing methods for reasoning about spatial relationships among objects
* Understanding the interaction between low-level information and high-level knowledge and expectations
* Interpreting stereo images, e.g., for range and motion
* Understanding the interaction between an image and other information about the scene, e.g., written descriptions
* Determining terrain features: lakes, pebbles, mud, quicksand.

ii. Natural Language Interpretation

Research on interpreting natural language is concerned with developing computer systems that can interact with a person in English (or another nonartificial language). One primary goal is to enable computers to use human languages rather than force humans to use computer languages.

Research is concerned with both written and spoken language and, although many of the problems are independent of the communication medium, the medium itself can present problems. We will first consider written language, then the added problems of speech.

There are many reasons for being able to develop computer systems that can interpret natural-language inputs. They can be grouped into two basic categories: improved human/machine interface and automatic interpretation of written text.

Improving the human/machine interface will make it simple for humans to

* Give commands to the computer--or robot
* Query data bases

* Conduct a dialog with an intelligent computer system.

The ability to automatically interpret text will enable the computer to

* Produce summaries of texts
* Provide better indexing methods for large bodies of texts
* Translate texts automatically or semi-automatically
* Integrate text information with other information.

(1). Current Status

Natural language understanding systems that interpret individual (independent) sentences about a restricted subject area (e.g., data in a data base) are becoming available. They can accept sentences whose grammar is complex, with a reasonably large vocabulary, about a restricted subject area (e.g., the subject area covered by the data base). Their major limitation is that they cannot interpret a sentence whose meaning depends on the more general, dynamic context supplied by preceding sentences.

Commercial systems providing natural-language access to data bases are becoming available. Given the appropriate data in the data base they can answer questions such as:

* Which utility helicopters are mission ready?
* Which are operational?
* Are any transport helicopters mission ready?

However, these systems have limitations, among which are:

* They must be tailored to the data base and subject area.
* They only accept queries about facts in the data base, not about the contents of the data base, e.g., "What questions can you answer about helicopters?"
* Few computations can be performed on the data.
* The meaning of a sentence cannot depend on the context.

So, for example, after asking:

What is the status of squadron A?

If the user asks

What utility helicopters are ready?

the utterance will be interpreted as

"Which among <u>all</u> the helicopters are ready?"

not

"Which of squadron A's helicopters are ready?"

Data base access systems with more advanced capabilities are still in the research stages. These capabilities include:

* Easy adaptation to a new data base or new subject area.
* Replies to questions <u>about</u> the contents of the data base (e.g., what do you know about aircraft availability?).
* Answers to questions requiring computations (e.g., the time for a ship to get someplace).

(2). <u>Research Issues</u>

In addition to extending capabilities of natural language access to data bases, much of the current research in natural language is directed towards determining the ways in which the context of an utterance contributes to its meaning and developing methods for using contextual information when interpreting utterances. For example consider the following pairs of utterances:

Sam: The locknut should be tight.
Joe: I've done it

and

Sam: Has the air filter been removed?
Joe: I've done it

Although Joe's words are the same in both cases, and both state that some action has been completed, they each refer to different actions. In one case, tightening the locknut, in the other, removing the air filter. The meanings can only be determined by knowing what has been said and what is happening.

Some of the basic research issues being addressed are:

* Interpreting extended dialogs and texts (e.g., narratives, written reports) where the meaning depends on the context.
* Interpreting indirect or subtle utterances, such as recognizing that "Can you reach the salt?" is a request for the salt.
* Developing ways of expressing the more subtle meanings of sentences and texts.
* Interpreting language that is "ungrammatical", e.g., slang or dialects. (This is particularly of interest for spoken language.)

iii. Spoken Language

Commercial devices are available for recognizing a limited number of spoken words, generally fewer than 100 words. These systems are remarkably reliable and very useful for certain applications.

The principal limitations of these systems are:

* They must be trained for each speaker.
* They only recognize words spoken in isolation.
* They recognize a limited number of words.

Efforts to link isolated word recognition with the natural language understanding systems are now underway. The result would be a system that, for a limited subject area, and with some training, would respond to spoken English inputs.

Understanding connected speech (i.e., speech without pauses) with a reasonably large vocabulary will require further basic research in acoustics and linguistics as well as the natural language issues discussed above.

g. Generation

We have defined generation broadly to include those topics associated with generating actions and language. Under that heading we will discuss:

* Mobility
* Manipulation
* Language generation.

i. Mobility

Mobility can include both navigation and propulsion.

(1). Navigation

The basic problems associated with autonomous navigation include the following:

* Positioning and orientation.
* Obstacle and hazard detection, including terrain features that present problems to certain types of locomotion.
* Avoiding or detouring around obstacles in a path.
* Route planning and following.

Point positioning and orientation are central problems that are being addressed independent of the issues of autonomous navigation. We can safely assume that systems, such as navigational satellites, will be able to provide position information that is accurate to 10-100 meters. Reasonably simple computational techniques can be combined with data from such systems to determine the precise path a moving vehicle is following.

Detecting obstacles in a path can be a major problem. The requirements of a system for detecting obstacles depend greatly on the vehicle and the terrain. For example, a sturdy vehicle in flat, dry terrain may only need to detect large obstacles such as boulders or trees, which is a relatively simple task that might be done with existing techniques and sensors. Terrain features such as large pools of water, quicksand, mudholes, and dense vegetation present many more obstacles. Detecting some of these is more difficult and will require advancements in computational vision. Also, some vehicles are more sensitive to uneven ground. For example, legged vehicles may require a vision system that provides enough information to help decide where to place each foot.

Avoiding an obstacle can be a difficult problem, again depending on the terrain and the type of locomotion. When the obstacle is easily identified and stationary, and a simple detour is possible, then reasonably simple techniques can be used to navigate around it. However, detouring around some obstacles may require more global modifications to the route. For example, if a bridge across a river has become impassable, it may be necessary to find another bridge or find another means of crossing the river. This type of planning would require a more general ability to plan and follow routes.

Another problem is presented by obstacles that move. Avoiding the obstacle requires predicting its path and speed. If the movement is erratic and perhaps intended to cause problems, avoiding it could be difficult.

In the most general case, route planning and following requires deciding where to go, planning a good route to get there, and then following along that route, making changes as necessary to accommodate unanticipated obstacles or situations. Some systems will not require such sophistication, although almost any of them will require some ability to detect and avoid obstacles in a given path.

There are three points along the continuum of path planning abilities that are particularly significant for the Navy.

(1) In the simplest case, the entire route could be prespecified. Reasonably simple computations could be used to ensure that the vehicle stays on the route, correcting for any deviation from the planned path. The major navigational problem would be in detecting and avoiding obstacles along the way.

(2) Some or all of the route is not prespecified, although the starting and ending points are. In this case, the unspecified portions of the route would have to be planned. The planning techniques described above, probably blended with operations research techniques for finding routes, could be used.

(3) The most advanced capability is that of first deciding where to go, and then deciding how to get there. The decision about destination might be affected by the difficulty of getting there, so there could be some interaction between deciding the destination and finding a route. A system that performed this type of navigational planning would most likely incorporate a planning system such as described above.

Propulsion issues include the choice of a locomotion method and operation of the propulsion equipment, which involves input and output.

Choice of locomotion method may be either conventional or unconventional. Conventional locomotion methods include all those used by current Navy platforms--wheels and tracks for ground locomotion, fixed and rotary wings for flight, propellers and pumps for surface and subsurface water travel. These would serve perfectly well for most naval robotic applications requiring mobility. Naval operations at sea could utilize conventional airborne or waterborne platforms, while wheeled vehicles would meet most mobility needs on board carriers and on naval air bases.

There are, however, a number of special situations in which no conventional locomotion methods are effective. Robotics research has led to some new and unconventional methods that may be. These include the use of mechanical legs for travel over extremely rough terrain, fins and novel actuators for silent subsurface travel, and tunneling equipment for subsurface ground mobility. Other unconventional modes of locomotion not requiring robotic technology are also likely to be useful. These include ground effect machines (hovercraft), hydrofoils, and balloons.

The unconventional locomotion methods would be primarily useful in certain specialized situations in Marine Corps missions--particularly in assault, reconnaissance, and infiltration. This is because of the extremely hostile, varied, and unpredictable environments encountered and the frequency of countermobility measures.

(2). Current Status

Operating a locomotion system involves controlling the propulsion system and steering the vehicle. These tasks require different kinds of sensing and different computer control.

Capabilities. Controlling the propulsion system usually requires sensing conditions such as wheel slippage, and it can require rapid responses, such as control of ailerons. Interfacing the propulsion mechanisms to the controlling computer is a straightforward engineering task, but developing the software for controlling the mechanisms may be quite difficult. Some locomotion systems, such as common helicopters and laboratory legged vehicles, have such complex dynamics that controlling them automatically is currently impractical. Helicopter autopilots can only hover, for instance. Most walking vehicle research ignores two-legged and four-legged configurations and treats only the more stable six-legged case. Prototype walking vehicles today also move their legs very slowly to minimize dynamic effects in the control problem.

Steering involves sensing conditions immediately ahead of the vehicle, such as the direction of a road.* It requires somewhat slower responses, but correspondingly more computer processing.

Limitations. All current platforms have been designed for specific purposes and operating environments and cannot operate in other situations. For example, a surface tender may be unable to launch and recover submersible or airborne robot vehicles in extreme sea states. Wheeled vehicles may get stuck in shell craters on an airfield.

In many cases, the range or speed of existing propulsion systems is inadequate. Battery-powered submersibles, for example, have limited range and the weight of their batteries makes them quite sluggish in maneuvering. New technologies such as fuel cells may improve their performance.

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* Steering is often considered part of navigation. However, since steering problems are directly related to the type of locomotion, we mention them here, too.

Automatic steering methods are currently inadequate to keep a free-roving land vehicle on a conventional road. Laboratory systems have followed specific types of roadway at slow speeds, by monitoring a specific feature such as a painted centerline or a high-contrast road edge. They are easily confounded by bad weather, debris, bridges, and different road surfaces. Industrial automatic vehicles only follow routes that are plainly marked by special paint stripes, buried electrical cables, or other signals.

For the navy and marine corps missions, propulsion methods are needed that are suitable for use in

* Submarine nets, minefields, and other countermobility obstacles
* Wet gaps with steep banks, ice, and/or fast currents
* Mud, bogs, swamps, sand, and soft ground
* Built-up areas, including docks, narrow streets, rubble, and interiors of buildings
* Piping, ductwork, and bulkhead cavities on a ship or aircraft, tunnels, sewers, and other narrow channels.

In addition, many applications such as reconnaissance and infiltration will require highly miniaturized mobile AI/robotics systems. Small size will make them harder to detect and allow them to pass through many kinds of barriers. The smaller the vehicle, however, the more objects will be large enough to block its path, and the more important it will be to find high-mobility vehicle designs.

<u>Laboratory Prototypes</u>. Mobile robots of many types have been constructed. Some notable ones include the General Electric Walking Truck (a 4-legged vehicle teleoperated by an on-board operator), SRI's Shakey and the Hilare robot of L.A.A.S. in Toulouse, France (two self-navigating, self-propelled wheeled robots), the Navy's free-swimming submersible, and Israel's remotely-managed semi-autonomous drone aircraft. Cruise missiles might be included in this list, too.

Walking, or legged vehicles are most appropriate for some of the worst mobility conditions. Ohio State University (OSU) has conducted

most of the original American research on automatic control of such vehicles. Carnegie-Mellon University and M.I.T. have recently begun legged locomotion research projects, too. Russian, Yugoslavian, and Japanese scientists have done significant work on the subject for many years. Komatsu, for example, has developed an eight-legged vehicle for seabed locomotion that could be used for mining, drilling oil wells, or harvesting mineral nodules.

Even stranger locomotion methods will be practical with robotic techniques. A Japanese laboratory has already developed prototypes of mechanical "snakes" and "limpets" that could enter confined spaces where no conventional or legged vehicle could go.

(3). Research Issues

Recent laboratory research on mobility concerns such topics as sensorimotor learning, motion in fleets, steering wheeled vehicles, visual obstacle avoidance, and autonomous underwater robots.

ii. Manipulation

Manipulation is the use of mechanical arms and hands to move objects. Manipulation tasks are extremely varied, and often occur as part of a more complex robotic task. For example, consider the important but hazardous task of repairing shell craters on an airstrip under fire. This is a good application for a mobile robot. The manipulatory portion of its task might involve activities such as leveling rubble in the crater, installing reinforcing iron, pouring in quick-setting concrete or epoxy, and marking the crater's location for pilots to avoid until it hardened. This activity might be embedded in a more complex patrol activity in which the robot would navigate about the airstrip, locate craters, inform flight operations of their size and location, prioritize their repair, allocate its remaining repair materials, and co-ordinate its own movements with those of arriving and departing aircraft.

It is often useful to classify a manipulation task according to the performance characteristics required of the manipulator. Some important characteristics are the following:

(1) Manipulation process performed
(2) Complexity of sensing required
(3) Complexity of control algorithms required
(4) Type of hand or tool motion required
(5) Type of drive used by the manipulator's actuators
(6) Configuration of the manipulator's joints.

Three important <u>manipulation processes</u> are (1) continuous material deposition, (2) rigid object handling, and (3) part mating (assembly). Most industrial applications of robot manipulators fall into one of these categories.

Three different types of <u>sensing</u> that may be required are (1) no sensing, (2) simple sensing of go/nogo conditions, and (3) complex sensing of the presence, identity, position, orientation, motion, and/or integrity of objects.

At least five different levels of <u>control complexity</u> are used today:

(1) Teleoperation, in which a person operates the manipulator(s) by remote control, sometimes from a great distance,

(2) Limited-sequence manipulation, in which the manipulator makes a small number of different but prespecified motions automatically,

(3) Teach/replay, in which the system remembers motions performed during teleoperation and repeats them later automatically,

(4) Programmed manipulation, in which computer software moves the manipulator in complex but repetitious patterns

(5) Sensor-guided manipulation, in which the robotic system makes its own decisions about how to move or react to conditions and events around it from moment to moment. The decisions are based on general, preprogrammed rules written into its control software. This is the most powerful kind of control.

Manipulators usually need to make only two types of tool motion: either "point-to-point" or "continuous-path." In the former, starting, stopping, and "via" points can be specified, but not the tool's trajectory between them. In the latter, complete trajectories may be specified. Most tasks require either point-to-point only, or a mixture of the two types.

Most commercial manipulators use one of three kinds of drive system today: (1) electric motors, (2) hydraulic actuators, or (3) air cylinders. Only limited-sequence manipulators use the latter, driving each joint with full force into rugged limit stops at each end of their travel. Others use one of the first two kinds in each joint, and operate them with a position servo loop to move the joint precisely and smoothly. However, an unique manipulator that recently appeared on the market uses a sophisticated servo design that operates rotary pneumatic motors in each joint.

Finally, manipulators may be classified according to their joint configuration. There are (1) "anthropomorphic" (all rotary joints, such as the Unimation PUMA or Milacron T3), (2) cylindrical (like the Prab Versatran), (3) spherical (like the "tank turret"-shaped Unimate 2000), or (4) Cartesian (with three linear sliding joints arranged at right angles in the "X-Y-Z" directions, like the IBM RS1). A number of parallel-joint manipulators have recently been designed, too. Although descriptive classifications for them do not yet exist, at least one such manipulator resembles a tripod.

Different applications require different kinds of manipulators. Spraying usually requires an arm with a long reach (about 3 m), medium speed (about 1 m/second), low accuracy (about 1 cm), smooth and continuous motions, and no sensory feedback. Decontamination of vehicles and equipment would be an important spraying job for a robot.

Simple handling often requires a long reach (1-6 m), although smaller arms are also used for this purpose. It also requires high speed (1-3 m/second), moderate accuracy (6 mm), intermittent or "point-to-point" motions, and simple sensory feedback if any. A typical simple

handling job would be to load a rocket into a launching rail under a wing, where the rail is in a known position with respect to the robot.

Dexterous manipulation tasks require heavy use of sensing and software, and are the most difficult kind. They usually require little reach (1 m) and moderate speed (1 m/sec), but very high accuracy (1 mm or better) and a variety of different types of motion (point-to-point, continuous, straight-line, sensor-controlled, compliant, etc.). Some difficult manipulation tasks are assembly, disassembly, handling loose or non-rigid objects, and cooperating with people in a manipulation task. An extreme example of a dexterous manipulation task would be safing hung live ordnance . Slightly less difficult but almost as dangerous would be the removal of an ejection seat. These tasks are difficult because of inherent uncertainties--the objects involved might be damaged, unidentified, or not precisely positioned, for example. An intelligent robot might fail to perform a part of a task and have to try again or find a different way to perform it. Its sensors would allow it to know what it was working on and when something went wrong; its software would allow it to decide what to do in response.

Arc welding requires sensing of the weld joint and appropriate software to control the motion of the weld gun as well as other parameters in the welding schedule. It requires low speed (15 cm/second) but high accuracy (2 mm).

Teleoperation is useful when a task has great variability from repetition to repetition, or when the task only needs to be done once. The task could be simple handling, a delicate assembly or disassembly operation, or some other kind. In teleoperation, a person (the operator) is in the control loop, rather than a computer. The operator moves a "master" arm and the robot or "slave" arm follows its motions. The operator may observe the slave arm directly or indirectly through a television camera. With most equipment the operator can feel objects that the slave arm touches; and can handle light or delicate objects very precisely. The slave arm can also be much larger than the master arm, and much stronger than the operator's arm. This extends the

operator's reach and allows him to handle heavy objects for long periods of time without becoming fatigued.

People have great ability to adapt to inaccuracies in the slave arm and to poor-quality tactile or visual feedback from the work area. In such situations, a person can almost always complete a manipulation task much faster, more precisely, and with less chance of failure than a computer can. Nevertheless, computer control can be useful.

In computer-augmented teleoperation, a computer assists the operator. It can take control for routine portions of a task and can override the operator if he makes a mistake. The computer can also perform rapid kinematic calculations to convert motions of the master arm's joints into motions of the slave arm's joints. This means that the master and slave arms can be different shapes and sizes. In particular, the master can be a light harness that the operator wears and carries with him.

An excellent opportunity for the Navy to use teleoperators is in the simultaneous refueling and rearming of aircraft. This is very hazardous and fatiguing. Teleoperation would make it possible for the crew to work in a separate room, far from the danger area--even in air-conditioned surroundings. Automatic fire-suppression equipment could be used that would not be safe to use with people in the area.

(1). Current Status

Teleoperators, limited-sequence manipulators, and teach/replay industrial robots have been available for about twenty years. Computer-controlled robots entered the marketplace about ten years ago. Commercial robots equipped with simple tactile and visual sensors have only become available in the last two years.

Capabilities. Thousands of robots all over the world now spray paint, palletize, spot weld, arc weld, cut, form, and inspect hundreds of different products. Many even operate other automatic machinery such as presses, molding machines, and numerically-controlled machine tools, just as people do.

For about five years now, commercial robot control software has been able to perform kinematic computations for a manipulator automatically. This means that one no longer has to manually coordinate the motions of all a manipulator's joints in order to make its hand move in a certain way. A typical computer-controlled manipulator today can automatically move its hand at a controlled speed in a straight line in any specified direction, move smoothly along a specified curved path, pass through a sequence of specified positions, control its hand orientation, etc. In particular, these kinematic computations allow it to adapt to arbitrarily-positioned workpieces and equipment. For example, a computer-controlled robot could insert a round into the breech of a gun that traverses or elevates between each round, provided the gun's displacements are made known to the computer.

Despite recent advances in sensing and control software, the vast majority of all robots still work on known objects that are held precisely in position for them. Most robots can make only the simplest kinds of decisions, few can sense, and dexterous manipulation in factories is still very rare.

Limitations. Very few robots today have sensors. This makes it difficult for them to handle objects that are not precisely positioned--if they are jumbled in a bin, for example, the robot cannot tell where to reach in order to grasp one. As another example, spraying robots today are all blind, so they can only spray objects that move precisely along a known path. A person can follow a swinging part with the spray gun, and make sure he doesn't miss any part of it. No robot can do this today.

Dexterous manipulation will require much better hands than are currently available for robots. Market forces are encouraging their development, however.

An industrial manipulator probably could not survive in a battle environment without some redesign. Some modifications that would be required are, for example:

* Militarize the computer. The controlling computers of most currently-used robots are not militarized. They would have to be either militarized or replaced by militarized computers with which the Navy is already familiar. The Navy is in a particularly favorable position compared to the other services in this regard because it happens to have standardized on a militarized version of a computer that is now widely used for robot control. This is the PDP-11 minicomputer series made by Digital Equipment Corporation (DEC). The Navy can therefore immediately acquire and make use of a great deal of public-domain robot control software. At least 50 man-years worth of such software has been developed by Universities such as Stanford, MIT, and Purdue, and by nonprofit research centers such as SRI International.
* Shield the hydraulic lines. Commercial hydraulically-operated robots usually do not have their hydraulic lines routed through their joints, where they would be protected. This is partly because designing the joints is difficult enough without adding the requirement for a clear passage, too.
* Simplify its maintenance procedures. In a factory, routine maintenance of most robots can be performed by an electrician with a little training. However, major repairs such as replacing a broken gear must often be performed by the vendor's specialists. A military robot should be constructed from easily-replaceable mechanical and electronic modules, even if it makes the robot more expensive.
* Automate calibration procedures. Many commercial manipulators require a complex initial calibration procedure at the time they are installed. In some cases this procedure requires special tooling and the services of the vendor's specialists. Even after installation, some robots also require the user to carry out a somewhat simpler calibration procedure every time the robot is turned on. A military robot should be designed so that it can perform any necessary calibration procedures completely automatically--preferably without moving, for safety. These procedures could be combined with autodiagnostic checks, and performed whenever the robot is not busy.

Manipulator programming software today has many shortcomings. Although the "training" procedures used in simple handling tasks could probably be adapted for casual use by nonspecialist sailors, today's robot programming languages (AL, VAL, RAIL, AML, etc.) are simply too difficult for them to learn and to use. Even a skilled programmer may

require several hours to teach a robot to perform a task that he could tell a person how to do in less than a minute. To overcome this drawback the robot must be made more intelligent.

The most advanced robot control software in factories today is still not very "resourceful" or "smart" about recovering from errors. It has no "common sense." A person must describe in extreme detail how to test for mishaps, and say exactly how the robot should react. It is utterly impractical for that person to anticipate all possible errors and plan for the corresponding contingencies.

The rapid arm motions that are needed to perform many kinds of tasks efficiently add difficult dynamic control problems to the simpler kinematic ones. Although rapid computational methods to solve dynamics problems have been developed, no commercial manipulators use them yet; instead, manufacturers of robots overdesign their products and operate them inefficiently to make sure they will be stable and to prevent them from shaking themselves to pieces. Their speed could be increased and their cost, weight, and energy consumption could be decreased by using lighter material (e.g., graphite fibers), drives with higher power density (e.g., direct-drive joints with samarium-cobalt magnets), and better control software (e.g., that adapts to the arm's increasing moment of inertia as it reaches out.).

Teleoperation is often the only way to perform certain industrial tasks with a robot arm today. This is also true for many military applications, and will probably continue to be so for some time.

Laboratory Prototypes. Novel manipulators have been built with opposed tendons, direct-drive motors, and redundant degrees of freedom. As mentioned above, a prototype robot hand with tactile sensing in each of three triple-jointed servo-controlled fingers was developed at Stanford University and has recently become a commercial product. Vision-controlled methods for the important application of handling objects supplied jumbled in a bin have been developed at the University of Rhode Island. Research on hand-eye coordination, multiple arm coordination, tactile sensing, and robot programming languages has been

in progress at Stanford University, SRI International, MIT, and Purdue for many years. Carnegie-Mellon University has recently set up a robotics laboratory, too.

Some American corporations developing advanced manipulators and sophisticated control systems for them include Unimation, Cincinnati Milacron, IBM, Texas Instruments, General Electric, Bridgeport Machine Tools, Thermwood, and IRI. Major foreign innovators include DEA and Olivetti in Italy, Kuka and Volkswagen in West Germany, Renault in France, and Hitachi, Fujitsu, Mitsubishi, and Kawasaki in Japan.

(2). Research Issues

Practical solutions are not yet available for many important theoretical problems in manipulator control. These include:

* Planning a manipulator's motions so that it will not hit anything.
* Staying within the work space of the manipulator.
* Staying within the limited range of motion of each joint.
* Avoiding "joint flips" (an abrupt change from one arm posture to another for a small change in hand position).
* Avoiding "singularities" (arm postures for which the joints experience something akin to gimbal lock in a gyroscope).
* Finding fast or energy-efficient ways to handle objects.
* Rapidly moving a manipulator that has long and slender links without exciting oscillations in it.
* Controlling a "tentacle" manipulator that has dozens or even hundreds of joints.
* Automatically deciding how to hold an object for a secure grip, or in order to be able to use it properly (e.g., it should hold a wrench by its handle, not its jaws).
* Simulating the operation of a manipulator graphically so that a person can tell what it is doing (in teleoperation) or what it will do (when programming it).

Manipulator programming languages are a major topic of research in many laboratories. There are at least a dozen languages now of some merit and a new one appears about every six months. Although there are now too many languages to discuss adequately in this report, we can list a few of the goals that their designers have been attempting to achieve.

* Ease of learning. Not everyone who has to use a robot is a skilled computer programmer.
* Ease of debugging. It should, for example, be possible to check out a new robot control program one step at a time to reduce the chance of an accident.
* Computing power. It should be easy to describe complex procedures that must frequently be performed. For example, an assembly robot should only have to be told where each part goes and it should be able to work out the required arm motions by itself. (Although much progress has been made, this is still a difficult research problem.)
* Extensibility. It should be easy to make the robot perform new actions, or tell it how to use a new sensor or tool.
* Low cost. The software available for programming the robot and the software that carries out that program should be able to run in a small, inexpensive computer.
* Parallelism. For efficiency, the language should allow programming for two or more robots working on different parts of a task at the same time.

No standards for manipulator programming languages have emerged as yet, and in fact researchers are still trying to determine what facilities should be included in such languages. In the next five years, there will be considerable research on using computer-aided design (CAD) systems to make it easier to specify tasks for a robot.

iii. Generating Information

Computers can be used to present information in various modes including:

* Written Language
* Spoken Language
* Graphics
* Pictures

One of the principal concerns in artificial intelligence is developing methods for tailoring the presentation of information to individuals. The presentation should take into account the needs, language abilities, and knowledge of the subject area of the person or persons. In many cases, generation means deciding both what to present

and how to present it. For example consider a repair advisor that leads a person through a repair task. For each step, the advisor must decide which information to give to the person. A very naive person may need considerable detail, a more sophisticated person would be bored by it. In deciding how to present information, there may, for example, be several ways of referring to a tool. If the person knows the tool's name then the name could be used, if not, it might be referred to as "the small red thing next to the toolchest". The decision may extend to other modes of output. For example, if a graphic display is available, a picture of the tool could be drawn rather than a verbal description given.

(1). Current Status

At present, most of the generation work in artificial intelligence is concerned with generating language. Quite a few systems have been developed to produce grammatical English (and other natural language) sentences. However, although a wide range of constructions can be produced, in most cases the choice of which construction (e.g., active or passive voice) is made arbitrarily. A few systems can produce stilted paragraphs about a restricted subject area.

A few researchers have addressed the problems of generating graphical images to express information instead of language. However, many research issues remain in this area.

iv. Research Issues

Some of the basic research issues associated with generating information include:

* Deciding which grammatical construction to use in a given situation.
* Deciding which words to use to convey a certain idea.
* Producing coherent bodies of text, paragraphs or more.
* Tailoring information to fit an individual's needs.

h. Reasoning

We have used the term "reasoning" to refer to the process of using information to make decisions, learn, plan, and carry out actions in the world.

There are many roles for reasoning including:

* Interpreting sensory information.
* Deciding what to output.
* Assimilating information.
* Recognizing (diagnosing) a situation, e.g., a medical problem, equipment failure, a failure of a robot to perform a task properly.
* Planning actions, e.g., assembly actions (for manipulators), navigation (path planning), battle strategy (not carried out by a system, but planned and told to a person).
* Monitoring the execution of plans and situations.

i. Assimilating Information

Being in any kind of changing environment and/or interacting with the environment means getting new information. That information must be incorporated into what is already known, tested against it, used to modify it, etc. Since one aspect of intelligence is the ability to cope with a new and/or changing situation, any intelligent system must be able to assimilate new information about its environment.

Since it is impossible to have complete and consistent information about everything, the ability to assimilate new information also requires the ability to detect and deal with inconsistent and incomplete information.

(1). Current Status

All artificial intelligence systems must assimilate information to some extent. One of the places the problem is addressed most directly is in multi-sensory integration, where information from multiple sensors is interpreted and combined in order to identify objects. Some

techniques have been developed for integrating new information, but basic research issues remain, primarily related to the problems of combining inconsistent or uncertain information.

ii. Expert Systems

'Expert systems' are computer programs that capture human expertise about a specialized subject area. Some example applications of expert systems are:

Medical Diagnosis
   INTERNIST, MYCIN, PUFF

Mineral Exploration
   PROSPECTOR

Diagnosis of Computer Faults
   DART

Electronic Troubleshooting
   SOPHIE

Analysis of Mechanical Structures
   SACON

Information Integration
   HASP .

The basic technique behind expert systems is to encode an expert's knowledge as rules stating the likelihood of a hypothesis based on available evidence. The expert system uses these rules and the available evidence to form hypotheses. If evidence is lacking, the expert system will ask for it.

An example rule might be:

```
IF THE JEEP WILL NOT START
        and
THE HORN WILL NOT WORK
        and
THE LIGHTS ARE VERY DIM
        then
THE BATTERY IS DEAD

with 90 PERCENT PROBABILITY   .
```

If an expert system has this rule and is told:

"THE JEEP WON'T START,"

the system will ask about the horn and lights and decide the likelihood that the battery is dead.

Recently some systems have been investigated that do not depend upon knowledge supplied by a human expert, but they do make use of detailed knowledge about the subject, such as design information. Such systems might better be called knowledge-base systems instead of expert systems. They are sometimes referred to as systems using causal models. DART, intended for diagnosing computer failures, is an example. It includes detailed knowledge of the logic of the computer that is used in order to determine the specific point of failure on the basis of the observed symptoms of computer malfunction

(1). <u>Current Status</u>

Expert systems are being tested in the areas of medicine, molecular genetics, and mineral exploration, to name a few. Within certain limitations these systems appear to perform as well as human experts. There are several commercial applications based on expert-system technology. One of these is R1, developed by Carnegie-Mellon University and Digital Equipment Corporation and used by DEC to generate automatically the detailed configuration, including cables, of VAX-11/780's.

Each expert system is custom-tailored to the subject area. It requires extensive interviewing of an expert, getting the expert's information into the computer, and verifying it, and sometimes writing new computer programs. There is extensive research required to improve the process of getting the human expert's knowledge into the computer and to design systems that do not require programming changes for each new subject area.

In general, the following are prerequisites for the success of a knowledge-based expert system:

* There must be at least one human expert acknowledged to perform the task well.
* The primary source of the expert's exceptional performance must be special knowledge, judgment, and experience.
* The expert must be able to explain the special knowledge and experience and the methods used to apply them to particular problems.
* The task must have a well-bounded domain of application.

(2). Research Issues

Basic research issues in expert systems include:

* The use of causal models, i.e., models of how something works to help determine why it has failed.
* Techniques for reasoning with incomplete, uncertain, and possibly conflicting information.
* Techniques for getting the proper information into rules.
* General-purpose expert systems that can handle a range of similar problems, e.g., work with many different kinds of mechanical equipment.

iii. Planning

Planning is concerned with developing computer systems that can combine sequences of actions for specific problems. Samples of planning problems include:

* Planning maintenance
* Repairing an aircraft
* Launching planes from a carrier
* Air defense
* Navigation
* Gathering Information.

Some planning research is directed towards developing methods for fully automatic planning, other research is on interactive planning, in which the decision making is shared by a combination of the person and

the computer. The actions that are planned can be carried out by either people or robots or both.

An artificial intelligence planning system starts with:

* Knowledge about the initial situation: e.g., gripe cards from an aircrew
* Facts about the world: e.g., replacing a defective component fixes a problem, acceptable limits for radar test data, symptoms of magnetron failure
* Actions that can be done: conduct a diagnostic test, remove a component, request a replacement, install the replacement
* Available objects: e.g., dummy load for radar antenna, spare cards for radar "box," automatic test equipment, repair robot, human technicians with various skills
* A goal: e.g., making aircraft operational, isolating fault, gaining access to test socket for test probe.

The system will produce (either by itself or with guidance from a person) a plan containing specific actions involving specific objects that will achieve the goal in this situation.

(1). Current Status

Planning is still in the research stages. The research is both theoretical in developing better methods for expressing knowledge about the world and reasoning about it, and more experimental in building systems to demonstrate some of the techniques that have been developed. Most of the experimental systems have been tested on small problems. Recent work at SRI on interactive planning is one attempt to address larger problems by sharing the decision-making between the human and machine.

One application of the interactive planner being developed at SRI is to the job of spotting aircraft on the deck of an aircraft carrier. A laboratory demonstration was prepared in cooperation with officers from the USS Carl Vinson. Further development of the experimental system has been proposed for use in training.

SRI is also developing a general-purpose fully-automatic planner, a much more ambitious undertaking. Its initial use will be to plan procedures for a group of robots to carry out in order to assemble different industrial products. Unlike other planners, it is being implemented in the PROLOG language. PROLOG was selected by the Japanese government as the basis for its national fifth-generation "intelligent" computer project.

(2). Research Issues

Research issues related to planning include:

* Reasoning about alternative actions that can be used to accomplish a goal or goals.
* Reasoning about actions in different situations.
* Representing spatial relationships and movements through space and reasoning about them.
* Evaluating alternative plans under varying circumstances.
* Planning and reasoning with uncertain, incomplete and/or inconsistent information.
* Reasoning about actions with strict time requirements. For example, some actions may have to be performed sequentially, or in parallel, or at specific times (e.g., night time), or merely at different times.
* Replanning quickly and efficiently when the situation changes.

iv. Monitoring Actions and Situations

Another aspect of reasoning is detecting that something significant has occurred (e.g., that an action has been performed or that a situation has changed). The key here is significant. Many things take place and are reported to a computer system; not all of them are significant all the time. In fact, the same events may be important to some people and not to others. The problem for an intelligent system is to decide when something is important.

We will consider three types of monitoring: monitoring the execution of planned actions, monitoring situations for change and recognizing plans.

(1). Plan-Execution Monitoring

Associated with planning is execution monitoring, that is, following the execution of a plan and replanning (if possible) when problems arise, or possibly gathering more information when needed. A monitoring system will look for specific situations to be sure that they have been achieved. For example, it would determine if a piece of equipment had arrived at a location it had planned to be moved.

We characterize the basic problem as follows: given some new information about the execution of an action or the current situation, determine how that information relates to the plan and the expected situation, and then decide if that information signals a problem, and, if so, what options are available for fixing it. The basic steps are: (1) find the problem (if there is one), (2) decide what is affected, and (3) determine alternative ways to fix the problem. Methods for fixing a problem include: picking another action to achieve the same goal, trying to achieve some larger goal another way, or deciding to skip the step entirely.

Research in this area is still in the basic stages. At present, most approaches assume a person supplies new information about the situation (unsolicited). However, for many problems the system must be able to acquire directly the information needed to be sure a plan is proceeding as expected, instead of relying on volunteered information. Planning to acquire information is a more difficult problem because it requires that the computer system have information about what situations are crucial to a plan's success and detect that those situations hold. Planning too many monitoring tasks could be burdensome, while planning too few might result in the failure to detect an unsuccessful execution of the plan.

(2). Situation Monitoring

Situation monitoring entails monitoring reported information in order to detect changes, for example, to detect movement of headquarters or changes in supply routes.

Some research has been devoted to this area, and techniques have been developed for detecting certain types of changes. Procedures known by names such as "demons"* can be set to be triggered whenever a certain type of information is asserted into a data base. However, there are still problems associated with specifying the conditions under which they should trigger. In general, it is quite difficult to specify what constitutes a change. For example, a change in supply route may not be signalled by a change of one ship's route, but in some cases three ships could signal a change. A system should not alert a person every time a ship detours, but it should not wait until the entire supply line has changed. Specifying when the change is significant and developing methods for detecting it are still research issues.

v. Plan Recognition

Plan recognition is the process of recognizing another's plan from knowledge of the situation and observations of actions. The ability to recognize another's plan is particularly important in adversary situations where actions are planned based on assumptions about the other side's intentions. Plan recognition is also important in natural language generation because often a person will ask a question or make a statement as part of some larger task. For example, if a person is told to use a ratchet wrench for some task, the question "What's a ratchet wrench?" may be asking "How can I identify a ratchet wrench?" rather than "Give me a dictionary definition of a ratchet wrench?" Responding appropriately to the question entails recognizing that having the wrench is part of the person's plan to do the task.

Research in plan recognition is in early stages and requires further basic research, particularly on the problem of inferring goals and intentions.

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* Not to be confused with RAND'S DEMONS (semiautonomous ground vehicles).

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Appendix B

UTILITY DATA BASE STRUCTURE FOR REPRESENTING MANPOWER REQUIREMENTS

CONTENTS

LIST OF TABLES

Appendix B

UTILITY DATA BASE STRUCTURE FOR REPRESENTING MANPOWER REQUIREMENTS

The utility data base structure was designed for use in a previous SRI analysis[1*] that was directed to the development of methodology for examining the effects of personnel shortfalls on Navy logistics personnel readiness. The data base structure consists of 18 utility pay grades, 7 utility skill groups, and a utility value for each pay grade/skill group combination. For this report, the data base structure was expanded to include monthly billet cost values for each pay grade/skill group combination.

1. Utility Pay Grades

The Utility Pay Grade component of the data base structure includes comparable representation of the full spectrum of officer, EP, and civilian pay grades. The equivalencing of the pay grades was based on the equivalent grade schedules used by the Naval Facilities Engineering Command in planning quarters and messing facilities for officers, EPs, and civilians.[2] Table A-1 presents a listing of the utility pay grades and the equivalency relationships with officer, EP, and the four major civilian grades.

2. Utility Skill Groups

The utility skill groups were derived from utility tables contained in the Decisions and Design, Inc. report on accrued utility of Navy enlisted personnel.[3] That report presented the results of a study conducted to determine the relative contribution to navy missions of the accrued experience of enlisted personnel. The report identified seven groupings of EP ratings from which relative utility data were generated. The utility groupings and numbers obtained were derived from analysis of interviews conducted with several experienced officers and petty officers,

*References are listed at the end of this appendix.

Table B-1

UTILITY PAY GRADE EQUIVALENCIES

Utility Pay Grade	Officer Pay Grades	EP Pay Grades	Civilian Pay Grades *			
			GS	WS	WL	WG
1		E-1	GS-0, GS-1			WG-1, WG-2
2		E-2	GS-2			WG-3, WG-4
3		E-3	GS-3			WG-5, WG-6
4		E-4	GS-4			WG-7, WG-8
5		E-5	GS-5	WS-1	WL-1	WG-9
6		E-6		WS-2, WS-3	WL-2	
7		E-7		WS-4	WL-3	WG-10
8		E-8	GS-6	WS-5, WS-6	WL-4	
9		E-9		WS-7	WL-5	WG-11
10	0-1, W-1, W-2		GS-7	WS-8, WS-9	WL-6, WL-7, WL-8	WG-12, WG-13
11	0-2, W-3, W-4		GS-8, GS-9	WS-10, WS-11	WL-9, WL-410, WL-11	WG-14
12	0-3		GS-10, GS-11	WS-12, WS-13	WL-12, WL-13, WL-14	WG-15
13	0-4		GS-12	WS-14, WS-15, WS-16	WL-15	
14	0-5		GS-13, GS-14	WS-17, WS-18, WS-19		
15	0-6		GS-15			
16			GS-16			
17	0-7 thru 0-11		GS-17			
18			GS-18			

* GS - General Schedule; WS-Federal Wage System, Supervisory; WL- Federal Wage System Leader; WG- Federal Wage System, Non-Supervisory

representing a fairly broad spectrum of duty types and service experience. Although these utility data were considered as being approximate in nature and not intended to be used for comparisons among EP ratings, it was felt that they did provide a sufficient and useful classification for the purposes of a utility data base structure.

The utility groupings established in that report are based on the following skill group definitions:

<u>Group A</u>: Operate complex weapons systems, make quick decisions, requires extensive formal and on-the-job training, strong combat role requirements.

<u>Group B</u>: Operate or maintain complex equipment, requires extensive formal and on-the-job training, strong combat role requirements.

<u>Group C</u>: Operate or maintain equipment of intermediate level of complexity, requires some formal training and much on-the-job training, strong combat role requirements.

<u>Group D</u>: Operate or maintain less complex support equipment and perform less technical tasks than ratings in Groups A, B and C, requires some formal and on-the-job training, some combat role requirements.

<u>Group E</u>: Perform administrative and support functions with some combat role requirements.

<u>Group F</u>: Perform administrative and support functions with little combat role requirements.

<u>Group G</u>: Perform useful support functions with no combat role requirements.

In that report, the following assignment of EP ratings to skill groups was established, where the EP ratings are defined in Table B-7:

Group A - FT, ST

Group B - AD, AQ, AT, AX, CTT, ES, ET, EW, GM, MT

Group C - ABE, AE, AM, AO, AW, BM, BT, CTM, EN, GS, HT, MM, MN, TD, TM

Group D - ABF, ABH, AS, CTI, CTO, CTR, IS, OS, OT, PR, QM, RM

Group E - CTA, HM, IM, ML, MR, OM, PM, SM, YN

Group F - AG, AK, AZ, BU, CE, CM, DK, DP, DT, EA, EP, LN, MA, MS, NC, PN, SK, SW, UT

Group G - DM, JO, LI, MU, PC, PH, SH

These skill groups were expanded to include officer designators, additional EP ratings, and civilian occupational codes. These assignments were based on our knowledge of the functions required of the various designators, ratings, and occupational codes and the manner in which they relate to the utility skill group's definitions. The resulting assignments are presented in Table B-2.

3. Utility Values

Basic utility values were established in the Decisions and Design, Inc. report. These utility values were established in a range from 0 to 100, and were tabulated for each utility skill group in arrays representing EP pay grade and length of service. The length of service variable was eliminated by choosing the maximum utility value for a pay grade over the various years of service. The resulting utility values obtained are presented in Table B-3. This array was expanded and normalized to include the 18 utility pay grades defined in Table B-1. This was accomplished by fitting least-square lines to the basic data for Utility Pay Grades 1 to 9 (E-1 to E-9) for each utility skill group and then normalizing the values to equal unity for the highest utility obtained for the least-squares extrapolation (Pay Grade 18 for Skill Group A). The resulting normalized utility values for the various utility skill groups and pay grades are presented in Table B-4.

Table B-2

UTILITY SKILL GROUP ASSIGNMENTS

Utility Skill Group	Aggregated Officer Designatora *	EP Ratinga †	Civilian White Collar Occupational Code Groups **	Civilian Blue-Collar Occupational Code Groups ††
A	111X, 112X, 116X, 117X 130X, 131X, 139X	FT, FTB, FTG, FTM, ST, STG, STS	None	None
B	100X, 105X, 110X, 113X, 114X, 118X, 119X, 132X, 137X, 152X, 7XXX, 8XXX	AC, AD, ADJ, ADR, AF, AN, AQ, AT, AV, AX, CTT, ET, ETN, ETR, EW, GM, GMG, GMM, GMT, MT, SN	None	None
C	140X, 141X, 144X, 146X, 150X, 151X	AB, ABE, AE, AM, AME, AMH, AMS, AO, AW, BM, BT, CT, CTM, EN, GS, GSE, GSM, HT, MM, MN, TD, TM	None	None
D	161X, 163X, 164X, 6XXX	ABF, ABH, AS, ASE, ASH, ASM, CTI, CTO, CTR, EM, IC, IS, OS, OT, PI, PR, PT, QM, RM	None	25, 26, 33, 40, 65, 66, 82, 83, 85, 86, 88
E	191X, 192X, 210X, 220X	APO, BR, CTA, DN, FN, HM, HN, IM, ML, MR, OM, PM, SM, YN	8, 11, 15	27, 28, 29, 57, 58, 59, 62, 67
F	180X, 193X, 230X, 290X, 310X, 510X	AG, AK, AZ, BU, CE, CM, CU, DK, DP, DT, EA, EO, EQ, LN, MA, MS, NC, PN, PO, SK, SW, UT	2,3,4,5,6,16,17, 19, 20, 21	34, 37, 38, 43, 45, 47, 48, 53, 54, 60, 61, 69, 87, 90
G	165X, 167X, 168X, 169X, 194X, 195X, 196X, 197X, 250X, 410X	DM, JO, LI, MU, PC, PH RP, SD, SH	0, 1, 7, 9, 10, 12, 14, 18, 22, 23	31, 32, 35, 36, 39, 41, 42, 44, 46, 50, 52, 55, 56, 70, 73, 74, 75, 76, 77, 84, 99

* Aggregated Officer Designators are defined in Table B-6

† EP ratings are defined in Table B-7

** Civilian White-Collar Occupational Code Groups are defined in Table B-8

†† Civilian Blue-Collar Occupational Code Groups are defined in Table B-9

Table B-3

BASIC PERSONNEL UTILITY DATA BASE

Pay Grade	Utility Group						
	A	B	C	D	E	F	G
E-1	11	11	11	11	11	10	8
E-2	19	20	20	20	20	14	10
E-3	29	29	29	29	29	19	14
E-4	52	52	52	43	38	22	14
E-5	67	67	67	52	48	31	17
E-6	81	81	81	62	52	31	17
E-7	95	90	81	67	57	38	21
E-8	100	95	86	73	63	42	21
E-9	100	95	86	73	63	42	21

Table B-4

NORMALIZED UTILITY VALUES

Utility Pay Grade	Utility Skill Group						
	A	B	C	D	E	F	G
1	.049	.049	.049	.049	.049	.044	.035
2	.088	.088	.088	.088	.088	.062	.044
3	.128	.128	.128	.128	.128	.084	.053
4	.230	.230	.230	.190	.168	.097	.062
5	.296	.296	.296	.230	.212	.122	.069
6	.358	.358	.327	.274	.230	.137	.075
7	.420	.398	.358	.296	.252	.168	.084
8	.442	.420	.380	.323	.278	.186	.093
9	.496	.475	.438	.359	.307	.199	.100
10	.552	.526	.484	.396	.337	.218	.108
11	.608	.580	.531	.433	.367	.237	.115
12	.664	.632	.577	.470	.397	.256	.123
13	.720	.684	.624	.507	.427	.275	.130
14	.776	.737	.670	.544	.457	.294	.138
15	.832	.790	.717	.581	.487	.313	.145
16	.888	.842	.763	.618	.517	.332	.153
17	.944	.895	.810	.655	.574	.351	.160
18	1.000	.947	.856	.692	.577	.370	.168

4. Monthly Billet Cost Values

Monthly billet cost values were established for the utility pay grade/ skill group combinations. These values were derived from billet cost data extracted from the two NPRDC reports[4,5] on officer and enlisted billet costs. Representative officer designators and enlisted ratings were chosen from each of the seven skill groups and initial monthly billet costs were tabulated for each pay grade/skill group combination. These tabulated values were then altered somewhat to provide a consistant scaling across skill groups and also vertically among the pay grades. The billet cost values were then increased in accordance with the ratio of the Consumer Price Indices for November 1980 and November 1983 to reflect estimated increases from the base period of the referenced reports. The resulting monthly billet cost values for the various utility skill groups and pay grades are presented in Table B-5.

Table B-5

MONTHLY BILLET COST VALUES
(Thousands of Dollars)

Utility Pay Grade	A	B	C	D	E	F	G
1	0.902	0.885	0.868	0.852	0.835	0.818	0.802
2	1.032	1.013	0.994	0.975	0.956	0.937	0.918
3	1.213	1.190	1.168	1.145	1.123	1.101	1.078
4	1.412	1.385	1.359	1.333	1.307	1.281	1.255
5	1.614	1.584	1.554	1.524	1.494	1.464	1.434
6	1.820	1.786	1.752	1.719	1.685	1.651	1.618
7	1.994	1.957	1.920	1.883	1.846	1.809	1.772
8	2.225	2.184	2.142	2.101	2.060	2.019	1.978
9	2.409	2.365	2.320	2.276	2.231	2.186	2.142
10	2.687	2.637	2.588	2.538	2.488	2.438	2.388
11	2.924	2.870	2.816	2.762	2.708	2.654	2.600
12	3.528	3.463	3.398	3.332	3.267	3.202	3.136
13	4.242	4.164	4.085	4.007	3.928	3.849	3.771
14	5.017	4.924	4.831	4.738	4.645	4.552	4.459
15	5.965	5.584	5.744	5.633	5.523	5.413	5.302
16	6.364	6.247	6.129	6.011	5.893	5.775	5.657
17	6.414	6.295	6.177	6.058	5.939	5.820	5.701
18	6.414	6.295	6.177	6.058	5.939	5.820	5.701

Table B-6

AGGREGATED OFFICER DESIGNATORS

Designator		Designator	
100X	Command Staff Officer	165X	Special Duty Officer (SDO) --Public Affairs
105X	Command Staff Officer	167X	Special Duty Officer (SDO) --Merchant Marine, Engr.
110X	Other Line Officer	168X	Special Duty Officer (SDO) --General Administration
111X	Surface Warfare Officer	169X	Special Duty Officer (SDO) --Merchant Marine, Comm.
112X	Submarine Warfare Officer	180X	Special Duty Officer (SDO) --Geophysics
113X	Special Warfare Officer	191X	Medical Corps Officer
114X	Special Operations Officer	192X	Dental Corps Officer
116X	Surface Warfare Officer	193X	Medical Service Corps Officer
117X	Submarine Warfare Officer	194X	Chaplain Corps
118X	Special Warfare Officer	195X	Judge Advocate General's Corps Officer
119X	Special Operations Officer	196X	Medical Corps Officer
130X	Aviation Officer (Pilot)	197X	Medical Corps Officer
131X	Aviation Officer (Pilot)	210X	Medical Corps Officer
132X	Aviation Flight Officer	220X	Dental Corps Officer
137X	Aviation Flight Officer	230X	Medical Service Corps Officer
139X	Aviation Officer (Pilot)	250X	Judge Advocate General's Corps Officer
140X	Engineering Duty Officer	290X	Nurse Corps Officer
141X	Engineering Duty Officer	310X	Supply Corps Officer
144X	Engineering Duty Officer	410X	Chaplain Corps Officer
146X	Engineering Duty Officer	510X	Civil Engineer Corps Officer
150X	(Unknown)	6XXX	Line-Limited Duty Officer
151X	Aviation Engineering Duty Officer	7XXX	Warrant Officer
152X	Aviation Maintenance Duty Officer	8XXX	Warrant Officer
161X	Special Duty Officer (SDO) --Crypto		
163X	Special Duty Officer (SDO) --Intelligence/Photo		
164X	Special Duty Officer (SDO) --Intelligence /Photo		

Table B-7

ENLISTED PERSONNEL RATINGS

Rating	Description	Rating	Description
AF	Aviation Boatswain's Mate	BM	Boatswain's Mate
ABE	Aviation Boatswain's Mate	BR	Boilermaker
	(Launching & Recovery Eqpmt.)	BT	Boiler Technician
ABF	Aviation Boatswain's Mate (Fuels)	BU	Builder
ABH	Aviation Boatswain's Mate	CE	Construction Electrician
	(Aircraft Handling)	CM	Construction Mechanic
AC	Air Controlman	CT	Communications Technician
AD	Aviation Machinist's Mate	CTA	Communications Technician
ADJ	Aviation Machinist's Mate		(Administration Branch)
	(Jet Engine Mechanic)	CTI	Communications Technician
ADR	Aviation Machinist's Mate		(Interpretive Branch)
	(Reciprocating Mechanic)	CTM	Communications Technician
AE	Aviation Electrician's Mate		(Maintenance Branch)
AF	Aircraft Maintenance Man	CTO	Communications Technician
	(E-9 only)		(Communications Branch)
AG	Aerographer's Mate	CTR	Communications Technician
AK	Aviation Storekeeper		(Collection Branch)
AM	Aviation Structural Mechanic	CTT	Communications Technician
AME	Aviation Structural Mechanic		(Technical Branch)
	(Safety Equipment)	CU	Constructionman (E-9 only)
AMH	Aviation Structural Mechanic	DK	Disbursing Clerk
	(Hydraulics)	DM	Illustrator Draftsman
AMS	Aviation Structural Mechanic	DN	Dentalman
	(Structures)	DP	Data Processing Technician
AN	Airman	DS	Data Systems Technician
AO	Aviation Ordnanceman	DT	Dental Technician
APO	Aviation Petty Officer	EA	Engineering Aid
AQ	Aviation Fire Control Technician	EM	Electrician's Mate
AS	Aviation Support Equipment Tech.	EN	Engineman
ASE	Aviation Support Equipment	EO	Equipment Operator
	Technician (Electrical)	EQ	Equipmentman (E-9 only)
ASH	Aviation Support Equipment	ET	Electronics Technician
	Technician (Hydraulics &	ETN	Electronics Technician
	Structures)		(Unknown)
ASM	Aviation Support Equipment	ETR	Electronics Technician
	Technician (Mechanical)		(Unknown)
AT	Aviation Electronics Technician	EW	Electronics Warfare Technician
AV	Avionics Technician (E-9 only)	FN	Fireman
AW	Aviation Antisubmarine	FT	Fire Control Technician
	Warfare Operator	FTB	Fire Control Technician
AX	Aviation Antisubmarine		(Ballistic Missile Fire Control
	Warfare Technician	FTG	Fire Control Technician
AZ	Aviation Maintenance		(Gun Fire Control)
	Administrationman	FTM	Fire Control Technician
			(Surface Missile Fire Control

Table B-7 (Concluded)

Rating	Description
GM	Gunner's Mate
GMG	Gunner's Mate (Guns)
GMM	Gunner's Mate (Missiles)
GMT	Gunner's Mate (Technician)
GS	Gas Turbine System Technician
GSE	Gas Turbine System Technician (Electrical)
GSM	Gas Turbine System Technician (Mechanical)
HM	Hospital Corpsman
HN	Hospitalman
HT	Hull Maintenance Technician
IC	Interior Communications Eletrician (includes EMCM)
IM	Instrumentman (includes PICM)
IS	Intelligence Specialist
JO	Journalist
LI	Lithographer
LN	Legalman
MA	Master-At-Arms
ML	Molder
MM	Machinist's Mate
MN	Mineman
MR	Machinery Repairman
MS	Mess Management Specialist
MT	Missile Technician
MU	Musician
NC	Navy Counselor
OM	Opticalman (includes PICM)
OS	Operations Specialist
OT	Ocean Systems Technician
PC	Postal Clerk
PH	Photographer's Mate
PI	Precision Instrumentman (E-9 only)
PM	Patternmaker (includes MLCM)
PN	Personnelman
PO	Petty Officer
PR	Aircrew Survival Equipmentman
PT	Photo Intelligence Technician
QM	Quartermaster
RM	Radioman
RP	Religious Program Specialist
SD	Steward
SH	Ship's Serviceman
SK	Storekeeper
SM	Signalman
SN	Seaman
ST	Sonar Technician
STG	Sonar Technician (Surface)
STS	Sonar Technician (Submarine)
SW	Steelworker (includes CUCM)
TD	Tradesman
TM	Torpedoman's Mate
UT	Utilitiesman
YN	Yeoman

Table B-8

CIVILIAN WHITE-COLLAR OCCUPATIONAL CODE GROUPS

Occupational Code Group*	Description
0	Miscellaneous Occupations
1	Social Science, Psychology and Welfare
2	Personnel Management and Industrial Relations
3	General Administrative, Clerical, and Office Services
4	Biological Sciences
5	Accounting and Budget
6	Medical, Hospital, Dental, and Public Health
7	Veterinary Medical Science
8	Engineering Architecture
9	Legal and Kindred
10	Information and Arts
11	Business and Industry
12	Copyright, Patent, and Trade-Mark
13	Physical Sciences
14	Library and Archives
15	Mathematics and Statistics
16	Equipment, Facilities, and Service
17	Education
18	Investigation
19	Quality Assurance, Inspection, and Grading
20	Supply
21	Transportation
22	Unspecified
23	Postal Operations

* Group members should be multiplied by 100 to correspond with group numbers in Reference 8.

Table B-9

CIVILIAN BLUE-COLLAR OCCUPATIONAL CODE GROUPS

Occupational Code Group*	Description
25	Wire Communication Equipment Installation and Maintenance
26	Electronic Equipment Installation and Maintenance
27	Quartz Crystal Work
28	Electrical Installation and Maintenance
29	Electronic Equipment Operation
31	Fabric and Leather Work
32	Glass Work
33	Instrument Maintenance
34	Machine Tool Work
35	Manual Labor
36	Masonry, Plastering, and Roofing
37	Metal Processing
38	Metal Work
39	Motion Picture, Radio, Television, and Sound Recording Equipment Work
40	Optical Work
41	Painting and Paperhanging
42	Pipefitting
43	Plastic Work
44	Printing and Reproduction
45	Rubber Work
46	Woodwork
47	General Maintenance and Operations
48	General Equipment Maintenance
50	Agriculture, Forestry and Kindred
52	Miscellaneous Occupations
53	Fixed Industrial Maintenance
54	Fixed Industrial Equipment Operation
55	Quarry Work
56	Currency, Securities, Coin, and Medal Making
57	Mobile Industrial Equipment Operations
58	Mobile Industrial Equipment Maintenance
59	Marine Operations
60	Railroad Operations
61	Railroad Maintenance
62	Marine Maintenance
65	Ammunition and Explosives
66	Armament Work
67	Manufacture and Repair Shop Operations
69	Warehousing

Table B-9 (Concluded)

Occupational Code Group*	Description
70	Packing and Processing
73	Laundry and Dry Cleaning
74	Food Preparation and Serving
75	Medical Services
76	Merchandising and Personal Services
77	Animal Caretaking
82	Fluid Systems
83	Instrumentation
84	Reclamation Work
85	Aircraft Propeller Overhaul
86	Aircraft Engine Overhaul
87	Manufacturing, Repair and Industrial Support Supervision
88	Aircraft Overhaul
90	Film Processing
99	Blue-Collar Unspecified

* Group members should be multiplied by 1000 to correspond with group numbers in Reference 9.

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Appendix C

ASSESS COMPUTER PROGRAM

CONTENTS

Appendix C

ASSESS COMPUTER PROGRAM

This appendix presents a description of program inputs and a complete listing of the ASSESS Computer Program. This computer program is an implementation of the Cost-Benefit Model described in Chapter IV of the main body of this report. The program is written in the VAX-11 FORTRAN computer language, which is an extension of FORTRAN-77, for running on the DEC VAX-11/782 computer.

A description of the program inputs and their sequence is presented in Section 1. All program inputs are read in the program in free-field format. The program listing is presented in Section 2. The listing presents first the program execution routine PROGRAM ASSESS and then the applicable subroutines.

1. <u>Program Input Description</u>

RECORD TYPE	VARIABLE NAME	VARIABLE TYPE	DESCRIPTION
1	NPROJ	INT	NUMBER OF AI PROJECTS FOR ASSESSMENT. (NOTE: IPROJ IS USED FOR INDEXING)
REPEAT RECORD TYPES 2-7, IPROJ=1,NPROJ			
2	PROJNAME	C*20	AI PROJECT NAME (IPROJ)
3	MOSTART	INT	START MONTH OF PROJECT FROM PRESENT, I.E., EARLIEST STARTING MONTH WOULD BE MOSTART=1.
4	MONTHS	INT	MONTHS DURATION OF BASIC RESEARCH PHASE
	COST	REAL	TOTAL COST OF BASIC RESEARCH PHASE IN DOLLARS (UNITS OF USER CHOICE). UNITS MUST BE CONSISTENT THROUGHOUT INPUT.
	PS	REAL	PROBABILITY OF SUCCESS ASSOCIATED WITH BASIC RESEARCH PHASE.
5	MONTHS	INT	MONTHS DURATION OF EXPLORATORY DEVELOPMENT PHASE.
	COST	REAL	TOTAL COST OF EXPLORATORY DEVELOPMENT PHASE.
	PS	REAL	PROBABILITY OF SUCCESS ASSOCIATED WITH EXPLORATORY DEVELOPMENT PHASE
6	MONTHS	INT	MONTHS DURATION OF ADVANCED DEVELOPMENT PHASE.
	COST	REAL	TOTAL COST OF ADVANCED DEVELOPMENT PHASE.
	PS	REAL	PROBABILITY OF SUCCESS ASSOCIATED WITH ADVANCED DEVELOPMENT PHASE.
7	MONTHS	INT	MONTHS DURATION OF ENGINEERING DEVELOPMENT PHASE.
	COST	REAL	TOTAL COST OF ENGINEERING DEVELOPMENT PHASE.
	PS	REAL	PROBABILITY OF SUCCESS ASSOCIATED WITH ENGINEERING DEVELOPMENT PHASE.
END REPEAT RECORD TYPES 2-7			
8	NOM	INT	NUMBER OF ORGANIZATIONAL MAINTENANCE (OM) COMPONENTS AFFECTED.
	NIM	INT	NUMBER OF INTERMEDIATE MAINTENANCE (IM) COMPONENTS AFFECTED.
	NDM	INT	NUMBER OF DEPOT MAINTENANCE (DM) COMPONENTS AFFECTED.
9	NWCTOM	INT	NUMBER OF WORK CENTER TYPES AFFECTED BY AI PROJECTS AT ORGANIZATIONAL MAINTENANCE LEVEL.
	NWCTIM	INT	NUMBER OF WORK CENTER TYPES AFFECTED BY AI

			PROJECTS AT INTERMEDIATE MAINTENANCE LEVEL.
	NWCTDM	INT	NUMBER OF WORK CENTER TYPES AFFECTED BY AI PROJECTS AT DEPOT MAINTENANCE LEVEL.
10	PCMASOM	REAL	PROPORTION OF ALL MAINTENANCE ACTIONS PERFORMED AT ORGANIZATIONAL MAINTENANCE LEVEL WITH PRESENT SYSTEM.
	PCMASIM	REAL	PROPORTION OF ALL MAINTENANCE ACTIONS PERFORMED AT INTERMEDIATE MAINTENANCE LEVEL WITH PRESENT SYSTEM.
	PCMASDM	REAL	PROPORTION OF ALL MAINTENANCE ACTIONS PERFORMED AT DEPOT MAINTENANCE LEVEL WITH PRESENT SYSTEM.
11	TIMSAR	REAL	SHIPPING AND RECEIVING TIME FOR COMPONENTS REPAIRED AT INTERMEDIATE MAINTENANCE LEVEL.
	TDMSAR	REAL	SHIPPING AND RECEIVING TIME FOR COMPONENTS REPAIRED AT DEPOT MAINTENANCE LEVEL.
REPEAT RECORD TYPE 12-16, IWCT=1,NWCTOM+NWCTIM+NWCTDM			
12	IWCTNBR	INT	WORK CENTER NUMBER
	PCMAS	REAL	PROPORTION OF WORK CENTER'S MAINTENANCE LEVEL'S MAINTENANCE ACTIONS THAT GO THROUGH THIS WORK CENTER TYPE.
	TATOLD	REAL	TURNAROUND TIME AT THIS WORK CENTER WITH PRESENT SYSTEM.
13	WCTNAME	C*20	NAME FOR WORK CENTER TYPE IWCT.
14	NPERSCAT	INT	NUMBER OF PERSONNEL CATEGORIES FOR WORK CENTER TYPE IWCT OF PRESENT SYSTEM
REPEAT RECORD TYPE 15, 1,NPERSCAT			
15	IUPG	INT	UTILITY PAY GRADE OF PERSONNEL CATEGORY IN WORK CENTER TYPE IWCT OF PRESENT SYSTEM.
	IUSG	INT	UTILITY SKILL GROUP OF PERSONNEL CATEGORY IN WORK CENTER TYPE IWCT OF PRESENT SYSTEM.
	INBR	INT	NUMBER OF PERSONNEL IN PERSONNEL CATEGORY OF WORK CENTER TYPE IWCT OF PRESENT SYSTEM.
END REPEAT RECORD TYPE 15			
16	OCOLD	REAL	PRESENT OPERATING COST FOR WORK CENTER IWCT.
	RMOLD	REAL	PRESENT R&M COST FOR WORK CENTER IWCT.
	OHOLD	REAL	PRESENT OVERHEAD COST FOR WORK CENTER IWCT.
END REPEAT RECORD TYPES 12-16			
17	NPROJCOM	INT	NUMBER OF PROJECT COMBINATIONS TO BE ASSESSED.

(NOTE: IPROJCOM IS USED FOR INDEXING.)

REPEAT RECORD TYPES 18-27, IPROJCOM=1,NPROJCOM

18	COMNAME	C*20	NAME OF PROJECT COMBINATION IPROJCOM
19	COMB	C*9	PROJECT NUMBERS INCLUDED IN PROJECT COMBINATION IPROJCOM. E.G., COMB='246 ' MEANS THE COMBINATION CONSISTS OF PROJECTS 2, 4 AND 6. PROJECT NUMBERS MUST BE CONTIGUOUS.
20	MIMOCOM	INT	MONTHS DURATION OF MANUFACTURING AND INSTALLATION PHASE OF COMBINATION IPROJCOM.
21	MANUCOST	REAL	MANUFACTURING COST PER UNIT FOR PROJECT COMBINATION IPROJCOM.
	INSTCOST	REAL	INSTALLATION COST PER UNIT FOR PROJECT COMBINATION IPROJCOM.
22	PCMOMNEW	REAL	PROPORTION OF ALL MAINTENANCE ACTIONS PERFORMED AT ORGANIZATIONAL MAINTENANCE LEVEL WITH NEW SYSTEM.
	PCMIMNEW	REAL	PROPORTION OF ALL MAINTENANCE ACTIONS PERFORMED AT INTERMEDIATE MAINTENANCE LEVEL WITH NEW SYSTEM.
	PCMOMNEW	REAL	PROPORTION OF ALL MAINTENANCE ACTIONS PERFORMED AT DEPOT MAINTENANCE LEVEL WITH NEW SYSTEM.

REPEAT RECORD TYPES 23-28 UNTIL IWCT = 99

23	IWCT	INT	INDEX NUMBER OF WORK CENTER AFFECTED BY PROJECT COMBINATION IPROJCOM.
24	NWC	INT	NUMBER OF WORK CENTERS OF TYPE IWCT FOR PROJECT COMBINATION IPROJCOM AT WORK CENTER'S MAINTENANCE LEVEL.
	NWCSYS	INT	NUMBER OF UNITS PER WORK CENTER TYPE IWCT FOR PROJECT COMBINATION IPROJCOM AT WORK CENTER'S MAINTENANCE LEVEL.
25	NPERSCAT	INT	NUMBER OF PERSONNEL CATEGORIES FOR WORK CENTER TYPE IWCT AND PROJECT COMBINATION

REPEAT RECORD TYPE 26, 1,NPERSCAT

26	IUPG	INT	UTILITY PAY GRADE FOR PERSONNEL CATEGORY OF WORK CENTER TYPE IWCT AND PROJECT COMBINATION IWCT.
	IUSG	INT	UTILITY SKILL GROUP FOR PERSONNEL CATEGORY OF WORK CENTER TYPE IWCT AND PROJECT COMBINATION IWCT.
	INBR	INT	NUMBER OF PERSONNEL OF PERSONNEL CATEGORY IN WORK CENTER TYPE IWCT AND PROJECT COMBINATION IWCT.

```
END REPEAT RECORD TYPE 26

  27    WCOCOST      REAL    MONTHLY OPERATING COST FOR WORK CENTER TYPE
                             IWCT AND PROJECT COMBINATION IPROJCOM

        WCRMCOST     REAL    MONTHLY REPAIR AND MAINTENANCE COST FOR WORK
                             CENTER TYPE IWCT AND PROJECT COMBINATION
                             IPROJECOM.

        WCOHCOST     REAL    MONTHLY OVERHEAD COST FOR WORK CENTER TYPE
                             IWCT AND PROJECT COMBINATION IPROJCOM

  28    TAT          REAL    TURNAROUND TIME FOR WORK CENTER TYPE
                             IWCT AND PROJECT COMBINATION IPROJCOM.

END REPEAT RECORD TYPES 23-28
END REPEAT RECORD TYPES 18-28
```

2. Program Listing

a. Program ASSESS

```
      PROGRAM ASSESS
      CHARACTER*80 OUTFILE,INFILE
      CHARACTER*4 FLAG
C
C --- ANNOUNCE TITLE OF PROGRAM
      WRITE(6,6000)
 6000 FORMAT(20X,' P R O G R A M   A S S E S S  ')
C --- REQUEST OUTPUT FILENAME
   40 CALL GETFILE(OUTFILE,'OUT')
      IF(INOEX(OUTFILE,'ZZZZ') .GT. 0)GOTO 500
      OPEN(8,FILE=OUTFILE,STATUS='NEW',FORM='FORMATTEO',ERR=40)
C --- REQUEST INPUT FILENAME
   50 CALL GETFILE(INFILE,'IN')
      IF(INOEX(INFILE,'ZZZZ') .GT. 0)GOTO 500
      OPEN(7,FILE=INFILE,STATUS='OLO',REAOONLY,ERR=50)
C
C --- REAO NUMBER OF AI PROJECTS FOR ASSESSMENT
      REAO(7,*)NPROJ
      IF(NPROJ .GT. 10 .OR. NPROJ .LT. 1)THEN
        WRITE(6,6001) 'NUMBER OF PROJECTS'
 6001   FORMAT(1X,' ERROR IN INPUT FILE ENTRY:  ',A)
        GOTO 500
      ENO IF
      GTELOS=0.
C
C --- REAO IN ANO PROCESS RESEARCH ANO OEVELOPMENT AI OATA,
C --- ONE PROJECT AT A TIME
      OO I=1,NPROJ
C ---   REAO INPUT OATA FOR ONE PROJECT
        CALL REAORO(I,FLAG,GTELOS)
        IF(INOEX(FLAG,'ZZZZ') .GT. 0)GOTO 500
C ---   CALCULATE RESEARCH ANO OEVELOPMENT COSTS
        CALL CALCROP(I,GTELOS)
      ENO OO
C --- GIVE USER RESEARCH ANO OEVELOPMENT ASSESSMENT SUMMARY
      CALL GIVEOPT(NPROJ)
C
C --- REAO GENERAL INPUT OATA FOR PROJECT COMBINATIONS
      CALL REAOMI(NPROJCOM,FLAG)
      IF(INOEX(FLAG,'ZZZZ') .GT. 0)GOTO 500
C
C --- REAO PROJECT COMBINATION INPUT OATA AT PROJECT
C --- COMBINATION LEVEL
      OO IPROJCOM=1,NPROJCOM
        CALL REAOCOMB(IPROJCOM,FLAG)
        IF(INOEX(FLAG,'ZZZZ') .GT. 0)GOTO 500
C ---   REAO ANO CALCULATE PROJECT COMBINATION OATA AT
C ---   WORK CENTER LEVEL
        CALL REAOWC(IPROJCOM,FLAG)
        IF(INOEX(FLAG,'ZZZZ') .GT. 0)GOTO 500
C ---   COMPUTE TOTAL RESEARCH ANO OEVELOPMENT COSTS FOR
C ---   PROJECT COMBINATION
        CALL CALCROC(IPROJCOM,GTELOS)
C ---   COMPUTE MANUFACTURING ANO INSTALLATION INVESTMENT COSTS
        CALL CALCMII(IPROJCOM)
C ---   COMPUTE OIFFERENTIAL OUTPUTS FOR PROJECT
C ---   COMBINATION
        CALL CALCOIFO
C ---   WRITE OUTPUT TABLE ENTRY FOR
C ---   PROJECT COMBINATION.
        CALL WRITOC(IPROJCOM)
```

```
      END DO
  500 CONTINUE
      CLOSE(7)
      CLOSE(8)
      CALL SHOWFILE(INFILE,OUTFILE)
      END
```

b. Subroutine FILPROC

```
      SUBROUTINE FILPROC ( FIL, DATFIL )
C
C     FILPROC processes user entered files by:
C         1) stripping trailing blanks
C         2) appending '.DAT' if an extension is not specified
C
C
C       Data Declaration and Initialization
C
      INTEGER  PNTR, K, K1, IC, ID, DOT
      CHARACTER*80  FIL, DATFIL
C
C       Strip filename of trailing blanks
C
        DO 80  K = 1, 80
            K1 = 80 - K + 1
            IF ( FIL(K1:K1) .NE. ' ' ) THEN
                 PNTR = K1
                 GOTO 90
            ENDIF
80      CONTINUE
C
C       Determine whether user has specified extension ( ie. '.DAT');
C        if not, append '.DAT' (note: '.DAT' is the assumed file type).
C
90      DOT = 0
        DO 100  IC = 1, 4
            ID = PNTR - IC + 1
            IF ( FIL(ID:ID) .EQ. '.' ) THEN
                 DOT = 1
            ENDIF
100     CONTINUE
        IF ( DOT .EQ. 0 ) THEN
            DATFIL = FIL(1:PNTR) // '.DAT'
        ELSE
            DATFIL = FIL(1:PNTR)
        ENDIF
      RETURN
      END
```

c. Subroutine READRD

```
      SUBROUTINE READRD(IPROJ,FLAG,GTELDS)
C --- THIS MODULE READS INPUT DATA FOR ONE AI PROJECT USING UNIT 7
C --- AND STORES DATA IN APPROPRIATE ARRAYS CONTAINED IN COMMON
C --- BLOCKS THAT INCLUDE RESEARCH AND DEVELOPMENT COST INFORMATION.
      CHARACTER*4 FLAG
      INCLUDE '[ROBOT]CBRDDAT.INC/LIST'
```

```
      FLAG=' '
C --- READ AI PROJECT NAME
      READ(7,'(A)',END=500)PROJNAME(IPROJ)
C --- READ START MONTH FROM PRESENT(PRESENT=1)
      READ(7,*,END=500)MOSTART(IPROJ)
C --- READ RESEARCH AND DEVELOPMENT INPUT DATA FOR EACH PHASE
      DO I=1,4
C ---   READ NUMBER OF MONTHS DURATION, TOTAL DOLLARS AND
C ---   PROBABILITY OF SUCCESS
        READ(7,*,END=500)MONTHS(I,IPROJ),COST(I,IPROJ),PS(I,IPROJ)
      END DO
      RETURN
  500 CONTINUE
      WRITE(6,6001)
 6001 FORMAT(1X,' PREMATURE END OF FILE DURING READ')
      FLAG='ZZZZ'
      RETURN
      END
```

d. Subroutine READMI

```
      SUBROUTINE READMI(NPROJCOM,FLAG)
C --- THIS MODULE READS INPUT DATA FOR NUMBERS OF MAINTENANCE
C --- COMPONENTS AND WORK CENTER TYPES.  ALSO READS PRESENT
C --- WORK CENTER INPUT DATA AND NUMBER OF PROJECT COMBINATIONS
C --- TO BE ASSESSED.
      CHARACTER*4 FLAG
      INCLUDE '[ROBOT]CBMIDAT.INC/LIST'
      INCLUDE '[ROBOT]CBCOSTDAT.INC/LIST'
      FLAG=' '
C --- READ NUMBERS OF MAINTENANCE COMPONENTS AFFECTED
      READ(7,*,END=500)NOM,NIM,NDM
C
C --- READ IN AFFECTED WORK CENTER DATA FOR PROJECTS
C
C --- READ IN NUMBER OF WORK CENTER TYPES AT EACH MAINTENANCE LEVEL
C --- AFFECTED BY THE AI PROJECTS
      READ(7,*,END=500)NWCTOM,NWCTIM,NWCTDM
      NWCT=NWCTOM+NWCTIM+NWCTDM
      NWCTIM1=NWCTOM+1
      NWCTDM1=NWCTOM+NWCTIM+1
      IF(NWCT .GT. 40 .OR. NWCT .LT. 1)THEN
        WRITE(6,6001) ' NO. WORK CENTER TYPES'
 6001   FORMAT(1X,' ERROR IN INPUT FILE ENTRY:  ',A)
        GOTO 550
      END IF
C --- READ PROPORTIONS OF ALL MAINTENANCE ACTIONS PERFORMED
C --- AT ORGANIZATIONAL, INTERMEDIATE, AND DEPOT MAINTENANCE
C --- LEVELS.  READ SHIPPING AND RECEIVING TIMES FOR COMPONENTS
C --- REPAIRED AT INTERMEDIATE AND DEPOT MAINTENANCE LEVELS.
      READ(7,*,END=500)PCMASOM,PCMASIM,PCMASDM
      READ(7,*,END=500)TIMSAR,TDMSAR
      DO IWCT=1,NWCT
C ---   READ NAMES OF EACH WORK CENTER TYPE, PERCENT OF ITS
C ---   MAINTENANCE ACTIONS THAT GO THROUGH THIS WORK CENTER TYPE,
C ---   AND PRESENT TURNAROUND TIME FOR THIS WORK CENTER TYPE.
        READ(7,*,END=500)IWCTNBR,PCMAS(IWCT),TATOLD(IWCT)
        IF(IWCTNBR.NE.IWCT)GO TO 600
        READ(7,'(A)',END=500) WCTNAME(IWCT)
```

```
C ---    READ AND CALCULATE PRESENT WORK CENTER COSTS AND PERSONNEL
C ---    FACTORS.
C ---    READ NUMBER OF PERSONNEL CATEGORIES IN PRESENT
C ---    SYSTEM WORK CENTERS
         READ(7,*,END=500)NPERSCAT
         PERSOLD(IWCT)=0.
         UTILOLD(IWCT)=0.
         PCOLD(IWCT)=0.
         DO I=1,NPERSCAT
C ---      READ INDEX PAY GRADE, SKILL GROUP, NUMBER OF PERSONNEL
           READ(7,*,END=500) IUPG,IUSG,INBR
           CALL CALCUCPC(IUSG,IUPG,INBR,PERSOLD(IWCT),
     $          UTILOLD(IWCT),PCOLD(IWCT))
         END DO
         READ(7,*,END=500)DCOLD(IWCT),RMOLD(IWCT),DHOLD(IWCT)
       END DO
C --- READ NUMBER OF PROJECT COMBINATIONS TO BE ASSESSED
      READ(7,*,END=500) NPROJCOM
      IF(NPROJCOM .EQ. 0)GOTO 550
      RETURN
  500 CONTINUE
      WRITE(6,6002)
 6002 FORMAT(1X,' PREMATURE END OF FILE DURING READ')
  550 CONTINUE
      FLAG='ZZZZ'
      RETURN
  600 WRITE(6,6003)IWCT,IWCTNBR
 6003 FORMAT(1X,'WORK CENTER INDEX NOT EQUAL TO WORK CENTER NUMBER'/
     $       1X,'IWCT=',I2,2X,'IWCTNBR=',I2)
      FLAG = 'ZZZZ'
      RETURN
      END
```

e. Subroutine READCOMB

```
      SUBROUTINE READCOMB(IPROJCOM,FLAG)
C --- READ PROJECT COMBINATION NAME AND IDENTIFIER. READ
C --- MANUFACTURING AND INSTALLATION COST AND DURATION
C --- INPUT DATA AND NEW PROPORTIONS FOR LEVEL OF MAINTENANCE
C --- PERFORMANCE.
      CHARACTER*4 FLAG
      INCLUDE '[ROBOT]CBMIDAT.INC/LIST'
      FLAG=' '
C --- READ PROJECT COMBINATION NAME
      READ(7,'(A)',END=500) COMNAME(IPROJCOM)
C --- READ PROJECT COMBINATION IDENTIFIER
      READ(7,'(A)',END=500) COMB(IPROJCOM)
C --- READ MONTHS DURATION OF MANUFACTURING AND INSTALLATION
C --- PHASE.
      READ(7,*,END=500) MIMDCOM(IPROJCOM)
C --- READ MANUFACTURING AND INSTALLATION COST PER UNIT
      READ(7,*,END=500) MANUCOST(IPROJCOM),INSTCOST(IPROJCOM)
C --- READ NEW PROPORTIONS OF MAINTENANCE ACTIONS
C --- PERFORMED AT ORGANIZATIONAL, INTERMEDIATE, AND
C --- DEPOT MAINTENANCE LEVELS.
      READ(7,*,END=500)PCMOMNEW(IPROJCOM),PCMIMNEW(IPROJCOM),
     $                 PCMDMNEW(IPROJCOM)
      RETURN
  500 CONTINUE
```

```
      WRITE(6,6002)
 6002 FORMAT(1X,' PREMATURE END OF FILE DURING READ')
      FLAG='ZZZZ'
      RETURN
      END
```

f. Subroutine READWC

```
      SUBROUTINE READWC(IPROJCOM,FLAG)
C --- THIS MODULE READS PROJECT COMBINATION DATA AT WORK CENTER
C --- LEVEL.  IT THEN CALLS ROUTINES THAT CALCULATE WORK CENTER COSTS,
C --- PERSONNEL FACTORS, AND TURNAROUND TIMES.
      CHARACTER*4 FLAG
      INCLUDE '[ROBOT]CBMIDAT.INC/LIST'
      INCLUDE '[ROBOT]CBCOSTDAT.INC/LIST'
      FLAG=' '
C --- INITIALIZE CBCOSTDAT COMMON BLOCK DATA FOR WORK CENTERS
C --- OF PROJECT COMBINATION.
      CALL INITIALC
C ---   READ WORK CENTER DATA
   10   READ(7,*,END=500)IWCT
        IF(IWCT.EQ.99)RETURN
        READ(7,*,END=500)NWC(IPROJCOM,IWCT),NWCSYS(IPROJCOM,IWCT)
        IF(IWCT.LT.NWCTIM1)THEN
          NWC(IPROJCOM,IWCT)=NOM*NWC(IPROJCOM,IWCT)
        ELSE IF(IWCT.LT.NWCTDM1)THEN
          NWC(IPROJCOM,IWCT)=NIM*NWC(IPROJCOM,IWCT)
        ELSE IF(IWCT.LE.NWCT)THEN
          NWC(IPROJCOM,IWCT)=NDM*NWC(IPROJCOM,IWCT)
        ELSE
          GO TO 550
        END IF
          READ(7,*,END=500)NPERSCAT
          WCPERS=0.
          WCUTIL=0.
          WCPCOST=0.
          DO I=1,NPERSCAT
C ---       READ INDEX PAY GRADE, SKILL GROUP, NUMBER OF PERSONNEL
            READ(7,*,END=500)IUPG,IUSG,INBR
            CALL CALCUCPC(IUSG,IUPG,INBR,WCPERS,WCUTIL,WCPCOST)
          END DO
          READ(7,*,END=500)WCOCOST,WCRMCOST,WCOHCOST
          READ(7,*,END=500)TAT
C ---     CALCULATE AND INCREMENT WORK CENTER COSTS,PERSONNEL
C ---     FACTORS, AND TURNAROUND TIMES.
          CALL CALCWCC(IPROJCOM,IWCT)
        GO TO 10
  500 CONTINUE
      WRITE(6,6002)
 6002 FORMAT(1X,' PREMATURE END OF FILE DURING READ')
      FLAG='ZZZZ'
      RETURN
  550 CONTINUE
      WRITE(6,6003)IPROJCOM,IWCT
 6003 FORMAT(1X,'WORK CENTER INDEX GREATER THAN MAXIMUM'/
     $       1X,'IPROJCOM=',I2,2X,'IWCT=',I2)
      FLAG='ZZZZ'
      RETURN
      END
```

g. Subroutine CALCRDP

```
      SUBROUTINE CALCROP(IPRO.',GTELOS)
C --- THIS MOOULE CALCULATES R&O INVESTMENT COSTS FOR THE FIRST
C --- FOUR PHASES OF EACH AI PROJECT.  COSTS ARE STOREO AS
C --- COMMON BLOCK OATA.
      INCLUOE '[ROBOT]CBROOAT.INC/LIST'
C --- CALCULATE BASIC RESEARCH COSTS
      TIC(1,IPROJ)=COST(1,IPROJ)
      PF(1,IPROJ)=1.-PS(1,IPROJ)
      PQ(1,IPROJ)=PF(1,IPROJ)
      PST(IPROJ)=PS(1,IPROJ)
      ELOS(1,IPROJ)=TIC(1,IPROJ)*PF(1,IPROJ)
      TELOS(IPROJ)=ELOS(1,IPROJ)
      ISTART(1,IPROJ)=MOSTART(IPROJ)
      IENO(1,IPROJ)=ISTART(1,IPROJ)+MONTHS(1,IPROJ)-1
      INVMOS(IPROJ)=MONTHS(1,IPROJ)
C --- CALCULATE REMAINOER OF R&O INVESTMENT COSTS
      OO I=2,4
C ---   CALCULATE TOTAL INVESTMENT COST
        TIC(I,IPROJ)=TIC(I-1,IPROJ)+COST(I,IPROJ)
C ---   CALCULATE PROBABILITY OF QUITTING
        PF(I,IPROJ)=1.-PS(I,IPROJ)
        PQ(I,IPROJ)=PST(IPROJ)*PF(I,IPROJ)
C ---   CALCULATE PROBABILITY OF SUCCESS
        PST(IPROJ)=PST(IPROJ)*PS(I,IPROJ)
C ---   CALCULATE EXPECTEO LOSS
        ELOS(I,IPROJ)=TIC(I,IPROJ)*PQ(I,IPROJ)
        TELOS(IPROJ)=TELOS(IPROJ)+ELOS(I,IPROJ)
C ---   CALCULATE START AND ENO MONTH OF EACH INVESTMENT PHASE
        ISTART(I,IPROJ)=IENO(I-1,IPROJ)+1
        IENO(I,IPROJ)=IENO(I-1,IPROJ)+MONTHS(I,IPROJ)
        INVMOS(IPROJ)=INVMOS(IPROJ)+MONTHS(I,IPROJ)
      ENO OO
C --- CALCULATE TOTAL POSSIBLE INVESTMENT LOSS AND PROBABABILITY THAT
C --- PROJECT IS UNSUCCESSFUL.
      ELOS(5,IPROJ)=PST(IPROJ)*TIC(4,IPROJ)
      TELOS(IPROJ)=TELOS(IPROJ)+ELOS(5,IPROJ)
      GTELOS=GTELOS+TELOS(IPROJ)
      PQT(IPROJ)=1.-PST(IPROJ)
      RETURN
      ENO
```

h. Subroutine GIVEOPT

```
      SUBROUTINE GIVEOPT(NPROJ)
C --- THIS MODULE OISPLAYS R&O INVESTMENT COST STATISTICS FOR EACH
C --- PHASE BY PROJECT AND WRITES THEM TO THE OUTPUT FILE IN TABLE
C --- FORMAT.
      INCLUOE '[ROBOT]CBROOAT.INC/LIST'
      CHARACTER*2J UNOERLIN
      CHARACTER*10 PHASE(5)
      DATA UNOERLIN/'--------------------'/,
     $     PHASE/'BASIC RES.','EXPL. OEV.',' ADV. DEV.',' ENG. OEV.',
     $           'TOTAL PROJ'/
C --- WRITE HEAOING TO OUTPUT FILE
```

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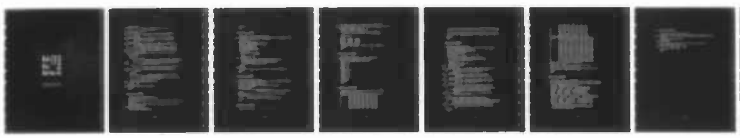
UNCLASSIFIED N00600-82-D-8362 F/G 5/1 NL



END

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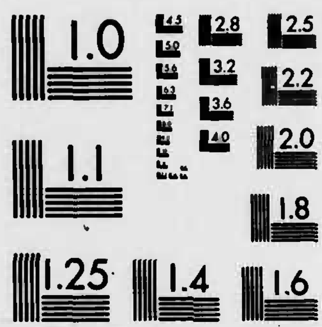

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
      WRITE(8,6001)
 6001 FORMAT(1X//T31,'SUMMARY OF RESEARCH AND DEVELOPMENT COSTS',
     $                ' BY R&D PROJECT'//)
C --- WRITE COLUMN HEADINGS
      WRITE(8,6002)
 6002 FORMAT(T4,'R&D',T19,'R&D',T57,'PERIOD',T68,'PROBABILITY',
     $       T84,'R&D',T93,'PROBABILITY',T107,'EXPECTED')
      WRITE(8,6003)
 6003 FORMAT(T2,'PROJECT',T17,'PROJECT',T36,'R&D',T46,'MONTHS',
     $       T55,'START',T62,'END',T72,'OF',T81,'INVESTMENT',
     $       T97,'OF',T106,'INVESTMENT')
      WRITE(8,6004)
 6004 FORMAT(T3,'NUMBER',T18,'NAME',T35,'PHASE',T45,'DURATION',
     $       T55,'MONTH',T61,'MONTH',T70,'SUCCESS',T82,'COST (K$)',
     $       T93,'TERMINATION',T107,'LOSS (K$)')
      WRITE(8,6005) UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN,
     $              UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN
 6005 FORMAT(1X,A7,2X,A20,2X,A10,2X,A8,2X,A5,1X,A5,2X,A11,2X,A10,
     $       2X,A11,2X,A10)
C --- WRITE R&D COST INFORMATION FOR EACH PHASE OF EACH PROJECT
      DO J=1,NPROJ
        WRITE(8,'(A1)')' '
        DO I=1,4
          IF(I .EQ. 1)THEN
            WRITE(8,6006)J,PROJNAME(J),PHASE(I),MONTHS(I,J),ISTART(I,J),
     $                   IEND(I,J),PS(I,J),COST(I,J),PQ(I,J),ELOS(I,J)
 6006       FORMAT(4X,I2,4X,A20,2X,A10,4X,I3,6X,I3,3X,I3,6X,F5.3,
     $             5X,F9.2,6X,F5.3,5X,F9.2)
          ELSE
            WRITE(8,6007)PHASE(I),MONTHS(I,J),ISTART(I,J),IEND(I,J),
     $                   PS(I,J),COST(I,J),PQ(I,J),ELOS(I,J)
 6007 FORMAT(T33,A10,4X,I3,6X,I3,3X,I3,6X,F5.3,5X,F9.2,6X,F5.3,
     $       5X,F9.2)
          END IF
        END DO
        WRITE(8,6005)' ',' ',UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN,
     $               UNDERLIN,UNDERLIN,UNDERLIN,' '
        WRITE(8,6007)PHASE(5),INVMOS(J),ISTART(1,J),IEND(4,J),PST(J),
     $               TIC(4,J),PQT(J),ELOS(5,J)
        WRITE(8,6009)UNDERLIN,TELOS(J)
 6009   FORMAT(T106,A10/T100,'TOTAL ',F9.2)
      END DO
      WRITE(6,6008)
 6008 FORMAT(2X,'R&D PHASE COMPLETED')
      RETURN
      END
```

i. <u>Subroutine GETFILE</u>

```
      SUBROUTINE GETFILE(FNAME,TYPE)
      CHARACTER*80 FILENAME,FNAME,MESSAGE
      CHARACTER*3 TYPE
C --- THIS SUBROUTINE PROMPTS USER FOR FILE NAME OF INPUT OR OUTPUT FILE
      FNAME=' '
      MESSAGE='Enter '//TYPE//'PUT data file name or ZZZZ to exit: '
      WRITE(6,6001)MESSAGE
 6001 FORMAT(1X,A45,$)
      READ(5,'(A80)')FILENAME
      CALL FILPROC(FILENAME,FNAME)
```

```
      RETURN
      END
```

j. Subroutine CALCRDC

```
      SUBROUTINE CALCRDC(IPROJCOM,GTELOS)
C --- THIS MODULE CALCULATES THE TOTAL RESEARCH AND DEVELOPMENT COSTS,
C --- INVESTMENT LOSSES AND O&M START MONTH.
      CHARACTER*1 P
      CHARACTER*9 PROJCOM
      INCLUDE '[ROBOT]CBMIDAT.INC/LIST'
      INCLUDE '[ROBOT]CBRDDAT.INC/LIST'
      RANDDCOST(IPROJCOM)=0.
      ISTARTMI(IPROJCOM)=0
      INVLOSS(IPROJCOM)=GTELOS
      PROJCOM=COMB(IPROJCOM)
      DO IPROJ=1,9
        P=PROJCOM(IPROJ:IPROJ)
        IF(P .EQ. ' ')GOTO 500
        IP=0
        DECODE(1,4000,P)IP
 4000   FORMAT(I1)
        RANDDCOST(IPROJCOM)=RANDDCOST(IPROJCOM)+TIC(4,IP)
        INVLOSS(IPROJCOM)=INVLOSS(IPROJCOM)-TELOS(IP)
        IF(ISTARTMI(IPROJCOM) .LT. IEND(4,IP))THEN
          ISTARTMI(IPROJCOM)=IEND(4,IP)
        END IF
      END DO
  500 CONTINUE
      ISTARTMI(IPROJCOM)=ISTARTMI(IPROJCOM)+MIMOCOM(IPROJCOM)+1
      RETURN
      END
```

k. Subroutine CALCMII

```
      SUBROUTINE CALCMII(IPROJCOM)
C --- THIS MODULE COMPUTES MANUFACTURING AND INSTALLATION INVESTMENT
C --- COSTS FOR ONE PROJECT COMBINATION.
      INCLUDE '[ROBOT]CBMIDAT.INC/LIST'
C --- COMPUTE TOTAL EQUIPMENTS FOR PROJECT COMBINATION
      TOTEQUIP(IPROJCOM)=0
      DO IWCT=1,NWCT
        TOTEQUIP(IPROJCOM)=TOTEQUIP(IPROJCOM) +
     $                   NWC(IPROJCOM,IWCT)*NWCSYS(IPROJCOM,IWCT)
      END DO
C --- COMPUTE MANUFACTURING AND INSTALLATION COST FOR PROJECT
C --- COMBINATION.
      MANDICOST(IPROJCOM)=TOTEQUIP(IPROJCOM) *
     $         (MANUCOST(IPROJCOM) + INSTCOST(IPROJCOM))
      RETURN
      END
```

l. Subroutine CALCDIFO

```
      SUBROUTINE CALCDIFO
```

```
C --- THIS MODULE COMPUTES THE DIFFERENTIAL OUTPUTS FOR
C --- ONE PROJECT COMBINATION (OPERATING COSTS/PERSONNEL ALLOCATIONS/
C --- PERSONNEL AVERAGE UTILITY)
      INCLUDE '[ROBOT]CBCOSTDAT.INC/LIST'
      PERSDIFF = TOTPERS - TPERSOLD
      IF (TOTPERS .NE. 0 .AND. TPERSOLD .NE. 0)THEN
        AUTILDIFF= TOTUTIL/TOTPERS - TUTILOLD/TPERSOLD
      ELSE
        AUTILDIFF=0.
      END IF
      PCDIFF = PCNEW - TPCOLD
      OCDIFF = OCNEW - TOCOLD
      RMDIFF = RMNEW - TRMOLD
      OHDIFF = OHNEW - TOHOLD
      TATDIFF=TATNEW-TTATOLD
      TOTDIFOC = 12.*(PCDIFF + OCDIFF + RMDIFF + OHDIFF)
      RETURN
      END
```

m. <u>Subroutine INITIALC</u>

```
      SUBROUTINE INITIALC
C --- THIS MODULE INITIALIZES PROJECT COMBINATION
C --- COST DATA IN COMMON BLOCK 'CBCOSTDAT'
      INCLUDE '[ROBOT]CBCOSTDAT.INC/LIST'
      TOTPERS = 0.
      TOTUTIL = 0.
      PCNEW = 0.
      OCNEW = 0.
      RMNEW = 0.
      OHNEW = 0.
      TPERSOLD = 0.
      TUTILOLD = 0.
      TPCOLD = 0.
      TOCOLD = 0.
      TRMOLD = 0.
      TOHOLD = 0.
      TATNEW=0.
      TTATOLD=0.
      RETURN
      END
```

n. <u>Subroutine CALCUCPC</u>

```
      SUBROUTINE CALCUCPC(ICOL,IROW,INBR,PERS,UTIL,PCOST)
      DIMENSION UC(7,18),PC(7,18)
C --- MONTHLY UTILITY COST TABLE (THOUSANDS OF DOLLARS)
      DATA UC /.049,.049,.049,.049,.049,.044,.035,
     $          .088,.088,.088,.088,.088,.062,.044,
     $          .128,.128,.128,.128,.128,.084,.053,
     $          .230,.230,.230,.190,.168,.097,.062,
     $          .296,.296,.296,.230,.212,.122,.069,
     $          .358,.358,.327,.274,.230,.137,.075,
     $          .420,.398,.358,.296,.252,.168,.084,
     $          .442,.420,.380,.323,.278,.136,.093,
     $          .496,.475,.438,.359,.307,.199,.100,
     $          .552,.526,.484,.396,.337,.218,.108,
```

```
    TATNEW=TATNEW+PCMIMNEW(IPROJCOM)*PCMAS(IWCT)*(TAT+2.*TIMSAR)
    TTATOLD=TTATOLD+PCMASIM*PCMAS(IWCT)*(TATOLD(IWCT)+2.*TIMSAR)
  ELSE
    TATNEW=TATNEW+PCMOMNEW(IPROJCOM)*PCMAS(IWCT)*(TAT+2.*TOMSAR)
    TTATOLD=TTATOLD+PCMASOM*PCMAS(IWCT)*(TATOLD(IWCT)+2.*TOMSAR)
  END IF
  RETURN
  END
```

o. Subroutine WRITEOC

```
      SUBROUTINE WRITOC(IPROJCOM)
C --- THIS SUBROUTINE PRINTS OUT RESULTS FOR THE OUTPUT TABLE.
      INCLUDE '[ROBOT]CBMIDAT.INC/LIST'
      INCLUDE '[ROBOT]CBCOSTDAT.INC/LIST'
      CHARACTER*132 STRING,TITLE
      CHARACTER*22 UNDERLIN
      DATA UNDERLIN/'----------------------'/
      IF(IPROJCOM .EQ. 1)THEN
C ---   WRITE TITLE AND COLUMN HEADINGS FOR TABLE
        TITLE='PROJECT COMBINATION COST-BENEFIT TABLE'
        CALL STRSTRIM(STRING,TITLE,L)
        STRING=' '
        STRING(66-L/2:132)=TITLE
        WRITE(8,6000)STRING
 6000   FORMAT('1'//1X,A//)
        WRITE(8,6001)
 6001 FORMAT(T27,'TOTAL',T37,'EXPECTED',T51,'TOTAL',T63,'TOTAL',
     $       T80,'DIFFERENTIAL',T93,'DIFFERENTIAL',T106,
     $       'DIFFERENTIAL',T119,'DIFFERENTIAL')
        WRITE(8,6002)
 6002   FORMAT(T28,'R&D',T36,'INVESTMENT',T51,'M&I',T61,
     $         'INVESTMENT',T74,'O&M',T83,'ANNUAL',T94,
     $         'TURNAROUND',T108,'NUMBER OF',T122,'AVERAGE')
        WRITE(8,6003)
 6003   FORMAT(T27,'COSTS',T39,'LOSS',T51,'COSTS',T63,'COSTS',
     $         T73,'START',T81,'O&MN COSTS',T97,'TIME',T108,
     $         'PERSONNEL',T122,'UTILITY')
        WRITE(8,6004)
 6004   FORMAT(T2,'PROJECT COMBINATION',T28,'(K$)',T39,'(K$)',
     $         T51,'(K$)',T64,'(K$)',T73,'MONTH',T84,'(K$)',
     $         T96,'(HOURS)',T108,'REQUIRED',T120,'PER PERSON')
        WRITE(8,6005)UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN,
     $       UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN,UNDERLIN,
     $       UNDERLIN
 6005 FORMAT(T2,A20,2X,A10,2X,A10,2X,A10,2X,A10,2X,A5,2X,A12,
     $      1X,A12,1X,A12,1X A12/)
      END IF
C --- WRITE PROJECT COMBINATION DIFFERENTIAL OUTPUTS
      WRITE(8,6006)COMNAME(IPROJCOM),RANDDCOST(IPROJCOM),
     $      INVLOSS(IPROJCOM),MANDICOST(IPROJCOM),RANDDCOST(IPROJCOM)+
     $      INVLOSS(IPROJCOM)+MANDICOST(IPROJCOM),ISTARTMI(IPROJCOM),
     $      TOTDIFOC,TATDIFF,PERSDIFF,AUTILDIFF,COMB(IPROJCOM)
 6006   FORMAT(1X,A20,2X,F9.2,3X,F9.2,3X,F9.2,3X,F9.2,3X,I5,
     $         3X,F9.2,4X,F9.2,5X,F8.1,5X,F8.5/1X,'R&D PROJS-',
     $         A9/)
      RETURN
      END
```

```
      $         .608,.580,.531,.433,.367,.237,.115,
      $         .664,.632,.577,.470,.397,.256,.123,
      $         .720,.684,.624,.507,.427,.275,.130,
      $         .776,.737,.670,.544,.457,.294,.138,
      $         .832,.790,.717,.581,.487,.313,.145,
      $         .888,.842,.763,.618,.517,.332,.153,
      $         .944,.895,.810,.655,.547,.351,.160,
      $        1.000,.947,.856,.692,.577,.370,.168/
C --- MONTHLY PERSONNEL COSTS (THOUSANDS OF DOLLARS)
      DATA PC /0.902,0.885,0.868,0.852,0.835,0.818,0.802,
      $         1.032,1.013,0.994,0.975,0.956,0.937,0.918,
      $         1.213,1.190,1.168,1.145,1.123,1.101,1.078,
      $         1.412,1.385,1.359,1.333,1.307,1.281,1.255,
      $         1.614,1.584,1.554,1.524,1.494,1.464,1.434,
      $         1.820,1.786,1.752,1.719,1.685,1.651,1.618,
      $         1.994,1.957,1.920,1.883,1.846,1.809,1.772,
      $         2.225,2.184,2.142,2.101,2.060,2.019,1.978,
      $         2.409,2.365,2.320,2.276,2.231,2.186,2.142,
      $         2.687,2.637,2.588,2.538,2.488,2.438,2.388,
      $         2.924,2.870,2.816,2.762,2.708,2.654,2.600,
      $         3.528,3.463,3.398,3.332,3.267,3.202,3.136,
      $         4.242,4.164,4.085,4.007,3.928,3.849,3.771,
      $         5.017,4.924,4.831,4.738,4.645,4.552,4.459,
      $         5.965,5.854,5.744,5.633,5.523,5.413,5.302,
      $         6.364,6.247,6.129,6.011,5.893,5.775,5.657,
      $         6.414,6.295,6.177,6.050,5.939,5.820,5.701,
      $         6.414,6.295,6.177,6.058,5.939,5.820,5.701/
C --- ACCUMULATE TOTAL NUMBER OF PERSONNEL
      PERS = PERS + INBR
C --- ACCUMULATE TOTAL UTILITY FROM UTILITY COST TABLE
      UTIL = UTIL + INBR * UC(ICOL,IROW)
C --- ACCUMULATE TOTAL PERSONNEL COST FROM PERSONNEL COST TABLE
      PCOST = PCOST + INBR * PC(ICOL,IROW)
      RETURN
      END
```

p. <u>Subroutine CALCWCC</u>

```
      SUBROUTINE CALCWCC(IPROJCOM,IWCT)
C --- THIS MODULE CALCULATES WORK CENTER COSTS, PERSONNEL FACTORS,
C --- AND TURNAROUND TIMES FOR PROJECT COMBINATION BEING ASSESSED.
      INCLUDE '[ROBOT]CBCOSTDAT.INC/LIST'
      INCLUDE '[ROBOT]CBMIDAT.INC/LIST'
      TOTPERS = TOTPERS + WCPERS * NWC(IPROJCOM,IWCT)
      TOTUTIL = TOTUTIL + WCUTIL * NWC(IPROJCOM,IWCT)
      PCNEW = PCNEW + WCPCOST * NWC(IPROJCOM,IWCT)
      OCNEW = OCNEW + WCOCOST * NWC(IPROJCOM,IWCT)
      RMNEW = RMNEW + WCRMCOST * NWC(IPROJCOM,IWCT)
      OMNEW = OMNEW + WCOMCOST * NWC(IPROJCOM,IWCT)
      TPERSOLD = TPERSOLD + PERSOLD(IWCT) * NWC(IPROJCOM,IWCT)
      TUTILOLD = TUTILOLD + UTILOLD(IWCT) * NWC(IPROJCOM,IWCT)
      TPCOLD = TPCOLD + PCOLD(IWCT) * NWC(IPROJCOM,IWCT)
      TOCOLD = TOCOLD + OCOLD(IWCT) * NWC(IPROJCOM,IWCT)
      TRMOLD = TRMOLD + RMOLD(IWCT) * NWC(IPROJCOM,IWCT)
      TOMOLD = TOMOLD + OMOLD(IWCT) * NWC(IPROJCOM,IWCT)
      IF(IWCT.LT.NWCTIM1)THEN
        TATNEW=TATNEW+PCMOMNEW(IPROJCOM)*PCMAS(IWCT)*TAT
        TTATOLD=TTATOLD+PCMASOM*PCMAS(IWCT)*TATOLD(IWCT)
      ELSE IF(IWCT.LT.NWCTOM1)THEN
```

q. Subroutine SHOWFILE

```
      SUBROUTINE SHOWFILE(INFILE,OUTFILE)
C --- THIS MODULE DISPLAYS THE INPUT AND OUTPUT FILE NAMES USED BY THE
C --- PROGRAM TO THE USER AFTER NORMAL OR ABNORMAL COMPLETION OF THE
C --- PROGRAM.
      CHARACTER*80 INFILE,OUTFILE
      WRITE(6,6000)
 6000 FORMAT(1X,
     $ ' The following files have been used by this program:')
      WRITE(6,6001)INFILE,OUTFILE
 6001 FORMAT(1X,' INPUT File:    ',A13/
     $        1X,' OUTPUT File:  ',A13)
      WRITE(6,'(1X,A4)')' BYE'
      RETURN
      END
```

END

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